~TRANSFORMERS~

Chapter 1 : Principles of Transformer

- Transforms AC electric power at same frequency & different voltage level .
- Classifications
  - 1-ϕ Transformer
  - Automatic Transformer [1-ϕ & 3- ϕ]
  - 3- ϕ Transformer
  - Instrument Transformer [Current Transformer (CT) , Potential Transformer (PT)]

- $e = \frac{d\lambda}{dt} \quad ; \lambda = \sum_{i=1}^{N} \phi_i = N\bar{\phi}$

Transformer Operations

1- **Transfer electric power from one circuit to another**
2- **Transfer electric power without any change in frequency**
3- **Transfer with the principle of electromagnetic induction**
4- **The two electrical circuit are linked by a mutual inductance**

Transformer Construction

1- **Two Windings**
2- **Laminated steel core**
3- **Suitable Container**
4- **Insulating medium**
5- **Bushings (porcelain or capacitor type)**

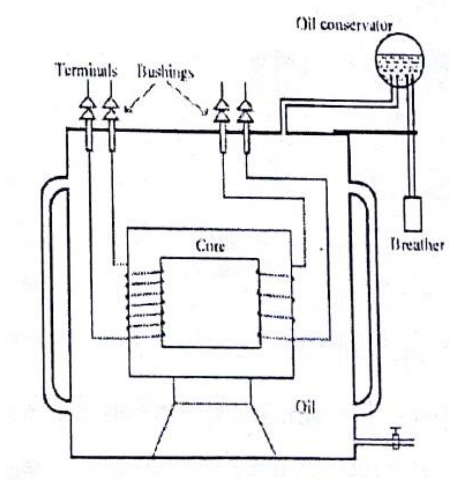
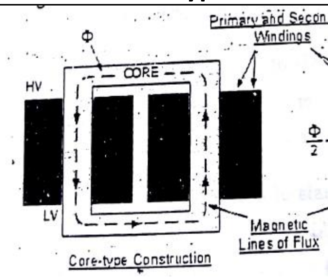
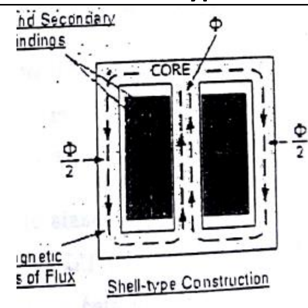


Fig. 1.2. Basic construction of the transformer

Transformer Types

Construction	
Core-Type	**Shell-Type**
 - Simple rectangular core - Cylindrical windings on two sides	 - Three-legged core - Windings wrapped around center leg

<u>On both types:</u> The High-Voltage winding is wrapped on top of the low-voltage winding

<u>Because:</u> 1- the low voltage winding is easier to insulate

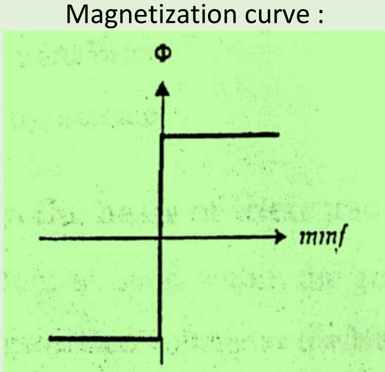
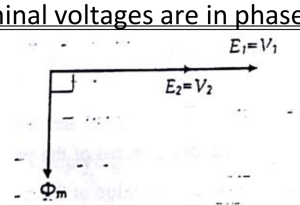
2- it reduces leakage flux

<u>((The selection between the two types is made by comparing the cost, as they have same ch/c))</u>

Most used is <u>**Shell-Type**</u> for <u>high voltage</u> app. And <u>multi winding design</u>

Purpose	
Step-up transformer	Step-down transformer
Supply	
1-ϕ	3-ϕ
Use	
Power (unit transformer) step up at the generation	**Transmission line transformer**

The Ideal Transformer

Winding resistance =0	***Copper losses = 0***
Leakage flux = 0	***Core losses = 0***
$\mu = \infty$	***Net mmf = 0 &*** $I_s = 0$
Magnetization curve : 	$mmf_{net} = 0$ $\therefore N_1 i_1 = N_2 i_2$ $V_1 = E_1$ $V_2 = E_2$ <u>It's terminal voltages are in phase as shown</u> 

<u>It's impossible to utilize an ideal transformer in practice</u>

EMF equation for ideal transformer

$$\phi(t) = \phi_m \sin(\omega t)$$

$$\therefore e_1 = N_1 \frac{d\phi(t)}{dt} = N_1 \omega \cos(\omega t) = E_{1m} \cos(\omega t)$$

The rms value $E_1 = \frac{N_1 \phi_m \omega}{\sqrt{2}} \angle 0$

$$\boldsymbol{E_1 = 4.44\, N_1 f \phi_m \angle 0°}$$

Same to secondary winding :

$$\boldsymbol{E_2 = 4.44\, N_2 f\, \phi_m \angle 0°}$$

Turns Ratio(a)

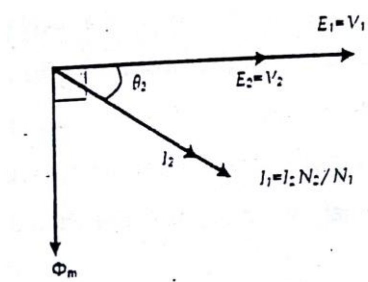
$$\boldsymbol{a = \frac{v_1}{v_2} = \frac{e_1}{e_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}}$$

Effect of Load Current

- We add a load
- Current i_2 will flow ; it's **magnitude** depends on **load impedence**
- ACT : It's **direction** is that to **weaken core flux** & **decrease $emf_{induced}$ at primary**
- REACT : the source **forces current i_1** in primary **to maintain flux as no-load value**

So $mmf_1 = mmf_2 \Rightarrow N_1 i_1 = N_2 i_2 \Rightarrow \frac{i_1}{i_2} = \frac{N_2}{N_1} = \frac{1}{a}$

Phasor diagram



The currents in the windings of an ideal transformer are inversely proportional to the turns of the windings.

$$p_{in} = p_{out} \Rightarrow v_1 i_1 = v_2 i_2 \Rightarrow V_1 I_2 = V_2 I_2$$

Although there is no physical connection between the load and the supply, as soon as the load consumes power, the same power is drawn from the supply. The transformer, therefore, provides a physical isolation between the load and supply while maintaining electrical continuity

POWERS

$$P_{in} = P_{out} = V_1 I_1 \cos\phi_1 = V_2 I_2 \cos\phi_2$$

$$Q_{in} = Q_{out} = V_1 I_1 \sin\phi_1 = V_2 I_2 \sin\phi_2$$

$$S_{in} = S_{out} = V_1 I_1 = V_2 I_2$$

Impedance Transfer

$$Z_2 = \frac{V_2}{I_2} \quad ; \quad Z_1 = \frac{V_1}{I_1}$$

$$V_1 = aV_2 \; ; \quad I_1 = \frac{I_2}{a}$$

$$Z_1 = a^2 \frac{V_2}{I_2}$$

$$\boxed{Z_1 = a^2 Z_2}$$

That equation states:

1- The load impedance from primary sides is a^2 it's actual value
2- Transformer can be used for **impedance matching** (a known impedance can be raised or lowered to match the rest of the circuit for maximum power transfer)

• هنهمل الـ (harmonic content) بسبب ان الـ $\boxed{\text{BH curve}}$ مش Linear لذلك نفترض انه Linear

عشان ألاشي الـ harmonics

$P_{in} = V_1 I_1 \cos\theta_1$

$P_{out} = V_2 I_2 \cos\theta_2$

الزاوية بين الـ V_1, I_1 : θ_1

$\cos\theta_1$: input power Factor.

$\cos\theta_2$: Load power Factor.

(لأن الـ losses مهملة) ⇓ ideal Transformer.

$$\frac{P_{in}}{P_{out}} = \frac{N_1}{N_2} \cdot \frac{N_2}{N_1} \cdot \frac{\cos\theta_1}{\cos\theta_2}$$

$\boxed{\cos\theta_1 = \cos\theta_2}$

note: يعني $\cos\theta_2 \neq \cos\theta_1$ كمفهوم ← وليس العكس →

لأن i_1 هو التابع لـ i_2 لأن نتيجة مرور i_2 هو اللي أجبر على مرور التيار i_1 ← وبالتالي $\cos\theta_1$ هي التابعة لـ $\cos\theta_2$

(الحل معروف عندي فيجب على مرور تيار i_2 لتوليد نفس عكس الفيض الأصلي فيجبر المصدر أنه يمرر i_1)

1. Power Factor input = Power Factor Load.
2. $\eta = 100\%$. ($P_{in} = P_{out}$) [neglect losses].
3. $\theta_1 = \theta_2$

Analysis of Ideal Transformer Circuit

We use the relations to transform one side of the transformer to the another

$$V_1 = aV_2 \ ; \quad I_1 = \frac{I_2}{a} \ ; Z_1 = a^2 \frac{V_2}{I_2}$$

To get a circuit without the transformer then analyze it

من خلال هذه النواتج من استخدام طريقة الـ Trans Former لاحظنا أن :-

1 هستخدم مساحة مقطع أقل للموصلات لأن التيار في حالة الـ Trans. قل.

2 الـ P_{Loss} هتقل

3 الجهد اللي هيوصل للحمل هيكون أقرب للقيمة اللي هو عاوزها.

مواتير الـ 3-Φ أقل في الحجم عن مواتير الـ 1-Φ

R_L b

* The impedence Transfer

لو عندي مصدر ومقاومة غير متساويتين وأنا عاوزهم متساويين علشان أحصل على (max. Power Transfer) هستخدم الـ Transformer علشان يشوفوا لهم متساويين.

Transformer Polarity

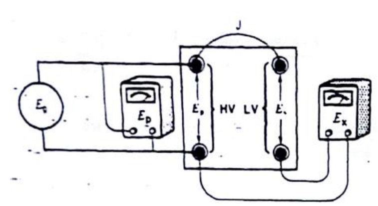
Identical Terminals: Produce flux in the same direction

We indicate identical terminals with a dot (.)

Determination of Polarity Experimentally

Method 1 (with AC)

1- Connect the HV winding to a suitable AC source
2- Connect Jumper J between adjacent HV and LV terminals
3- Connect voltmeter E_x between the other adjacent terminals
4- Connect another voltmeter E_p across the HV winding
5- If



$$E_x > E_P : The\ Polarity\ is\ \boldsymbol{Additive}$$
$$E_x < E_p : the\ polarity\ is\ \boldsymbol{Subtractive}$$

Test Explanation

When we used a jumper to connect E_p with E_s : the result is E_x

And I depends whether adding E_s to E_p is **Additive** or **Subtractive**

Note : even if the rating of transformer is large values , you can do the test with any voltage value below

Method 2 (with DC)

We connect the following circuit

Due to transient the voltage indicated will determine the polarity (in this figure)

- If pointer goes to a positive value, then it's **additive**
- If pointer goes to a negative value, then it's **subtractive**

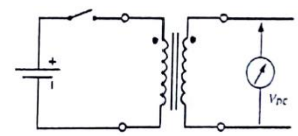


Fig. 1.13. The polarity determination with a battery

Application of Transformer Polarity

When we connect two transformers in **parallel** we must determine the polarity

To connect them right as (a) not wrong as (b)

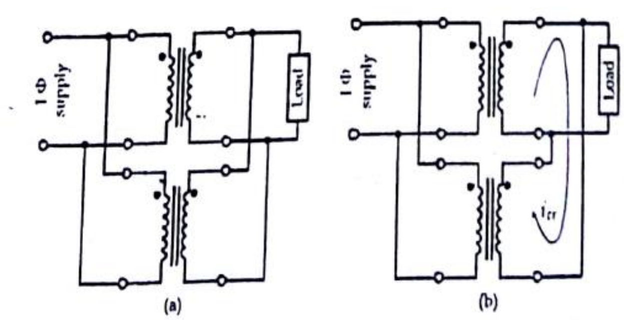


Fig. 1.14. Parallel operation of single-phase transformers (a) correct connection. (b) Wrong connection.

Transformer Rating

The name plate of a transformer provide information about:

1- The Apparent Power $S_r = VA\ (rated\ full\ load)$
2- Frequency(f)
3- Voltage Rating (V_p, V_s)
4- Turns Ratio (a)

Current is not written but can be obtained

$$I_p = \frac{S_r}{V_p} \ , I_s = \frac{S_r}{V_s}$$

The Voltage Rating importance in

1- Insulation
2- Volt per Turn (flux)

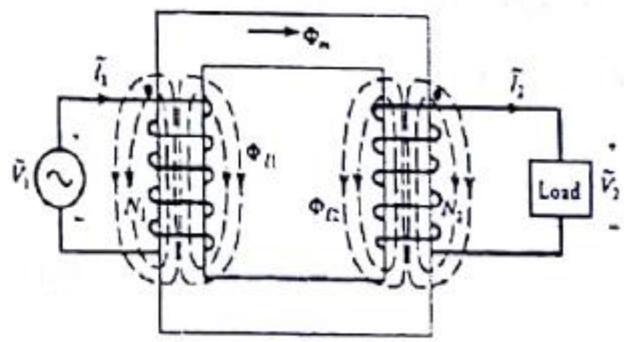
De-Rating

If Rated frequency is f_r and we want to operate at different frequency

Lower $f < f_r$	Higher $f > f_r$
Voltage input must also be decrease $V = \frac{f}{f_r} V_r$ If not : The peak flux ϕ_m will be too high	Voltage input can be increased $V = \frac{f}{f_r} V_r$ Only if increasing voltage won't cause insulating problem

Practical or Real Transformers

Effect of Leakage Flux on the voltage ratio across a transformer



$$we\ notice: \phi_1 = \phi_m + \phi_{L1}\ ;\ \phi_2 = \phi_m + \phi_{L2}$$

$$Faraday: v_1 = N_1 \frac{d}{dt}\phi_1 = \frac{N_1 d\phi_m}{dt} + \frac{N_1 d\phi_{L1}}{dt} = e_1 + e_{L1}$$

$$v_2 = N_2 \frac{d}{dt}\phi_2 = \frac{N_2 d\phi_m}{dt} + \frac{N_2 d\phi_{L2}}{dt} = e_2 + e_{L2}$$

$$\therefore \frac{e_1}{e_2} = \frac{N_1}{N_2} = a$$

$$but \frac{v_1}{v_2} \sim \frac{N_1}{N_2} = a\ (\,since\ in\ a\ well\ designed\ transformer\ \phi_m \gg \phi_{L1}\ \&\ \phi_m \gg \phi_{L2})$$

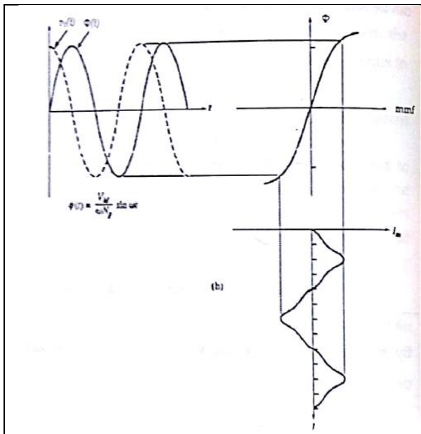
due to the leakage flux in primary and secondary windings the ratio of terminal voltages does not equal the turns ratio of the real transformer.

No-Load Current in a Real Transformer

Even if the secondary winding is left open (no-load condition) , the transformer still draws some current called **no-load** or **excitation current I_ϕ** (the current required to produce flux in the core) as permeability is finite and core loss exist

It has two components

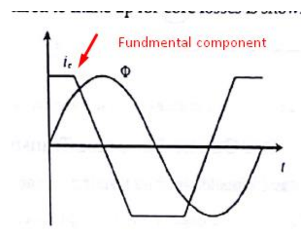
Magnetization Current I_m	**Core-Loss current I_C**
- Current necessary to produce mutual flux in the core $\bar{\phi} = \frac{1}{N_1}\int v_1 dt = \frac{1}{N_1}\int (V_m \cos\omega t)dt$ $\bar{\phi} = \frac{V_m}{\omega N_1}\sin\omega t$	- Current required to make up the hysteresis and eddy current losses of core - **The hysteresis loss** is required to accomplish the reorientation of the magnetic domains in the core during each cycle of the current applied to the core.



Note : 1-magnetization current is not sinusoidal
2-Once the peak flux reaches the saturation point in the curve a small increase in peak flux requires a very large increase in magnetization current
3- fundamental component of **Magnetization Current Lags Voltage by 90**

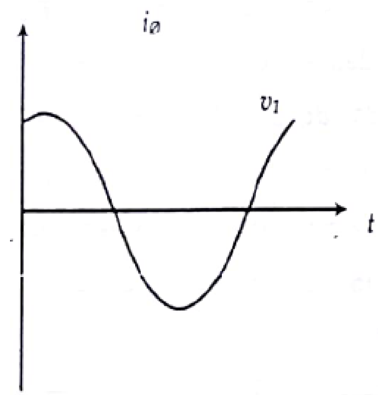
- eddy current generated in the core material. It goes into heating the iron core to solve it :
  - the core is made to many small strips or laminations
  - increase resistivity by adding silicon to the steel

since the eddy currents in the core are proportional to dϕ/dt, the eddy currents are largest when the flux in the core is passing through 0 Web.



Note : 1- core loss current is nonlinear because of the nonlinearity of hysteresis
2-the fundamental components of the core-loss current **is in phase with the voltage** applied to the core

The total excitation current :



← لـ Parasitic Capacitance { لوجود فرق جهد بين النقط اللي عندي ولكن بهمل تأثير الـ Capacitance لأن مساحة صغيرة

The Current Ratio on a transformer

$$mmf_{net} = N_1 i_1 - N_2 i_2 = \phi\Re \cong 0$$
$$\therefore N_1 i_1 \cong N_2 i_2$$
$$\frac{i_1}{i_2} = \frac{N_2}{N_1} = \frac{1}{a}$$

Note That The mmf in real transformer is nearly zero

Transformer Equivalent Circuit

(1) The Windings Resistance

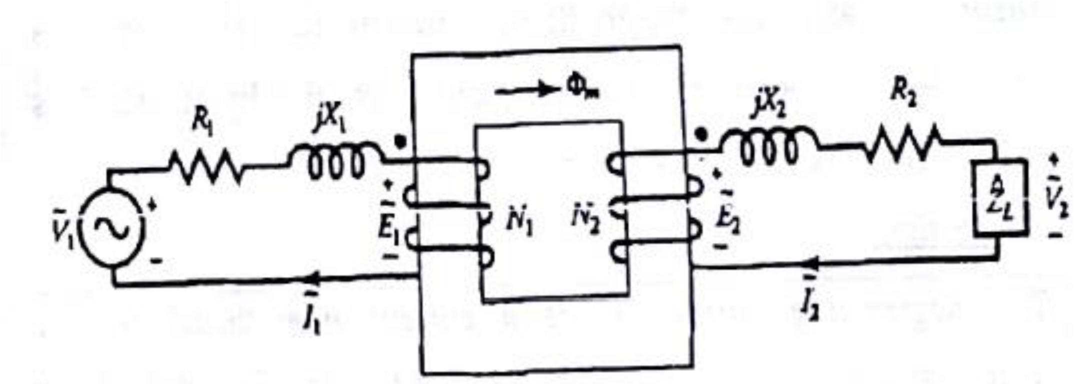
The windings has a resistance ! dah ! so we represent it by R1 and R2

$$so\ V_1 = E_1 + I_1 R_1$$
$$V_2 = E_2 - I_2 R_2$$

Including winding resistance dictates that :

1- The Power input must be greater than the power output
2- The terminal voltage is not equal to the induced emf
3- The efficiency (the ratio of power output to power input) of a real transformer is less than 100%

(2) The Leakage Flux



The leakage flux associated with either winding is responsible for the voltage drop across it Therefore, we can represent the voltage drop due to the leakage flux by a leakage reactance

$$so\ V_1 = E_1 + I_1(R_1 + jX_1)$$
$$V_2 = E_2 - I_2(R_2 + jX_2)$$

as

$$\frac{E_1}{E_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2} = a$$

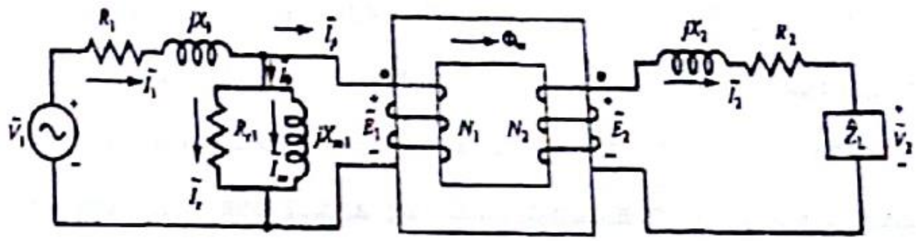
(3) Finite Permeability

Because it has finite permeability it draws current $I_\phi(Excitation\ Current)$ even if at no-load

$$I_\phi = I_m + I_c$$

1- $I_m \propto V$ "E" and lags it by 90 ° so it's represented by $X_m\ in\ parallel$
2- $I_c \propto V$ "E" and is in phase with it so it's represented by $R_c\ in\ Parallel$

3- Both are non-linear so the X and R are approximations



$$I_c = \frac{E_1}{R_{c1}} \;\; ; \;\; I_m = \frac{E_1}{jX_{m1}}$$

<u>NOTE :</u> The elements forming the excitation branch R_c and X_m are placed in the primary side. This is because the induced emf actually applied to the core is approximately equal to the input voltage to the transformer .

Referring the Equivalent Circuit

determined

PRIMARY

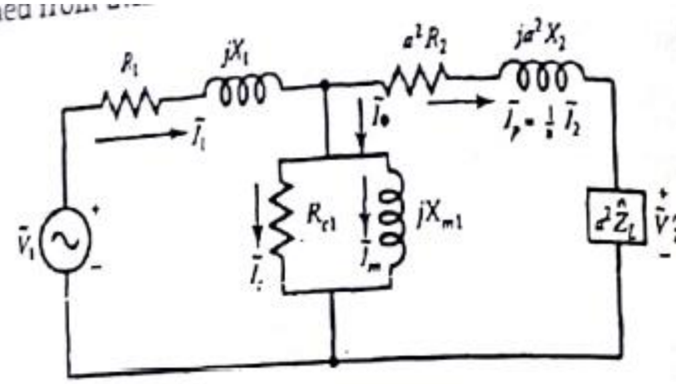


Fig. 2.10. The exact equivalent circuit as viewed from the primary side

SECONDARY

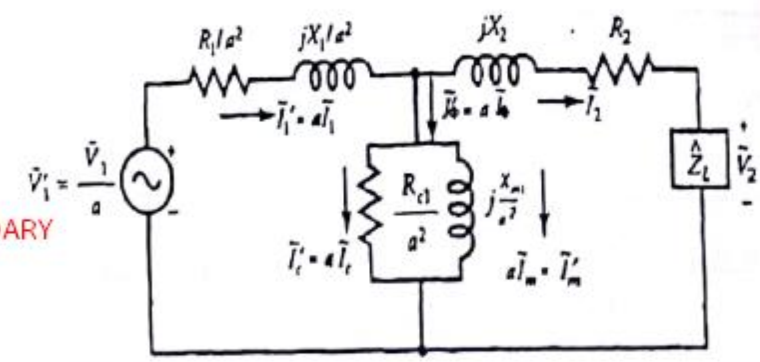
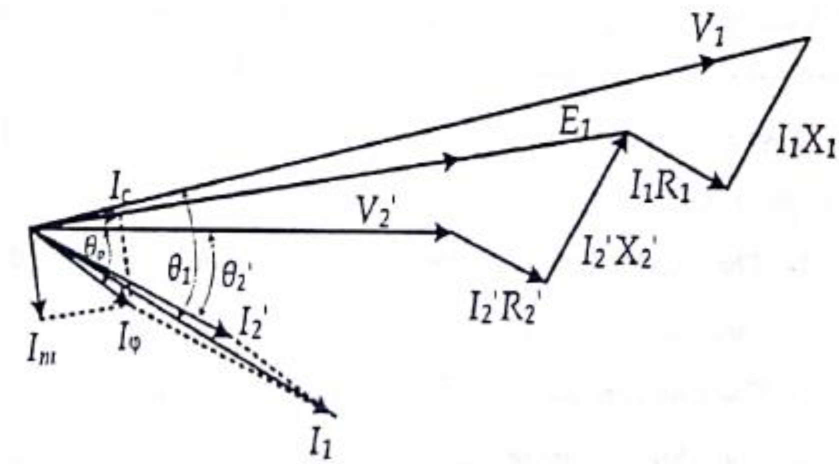


Fig. 2.11. The exact equivalent circuit as viewed from the secondary side of the transformer.

Phasor Diagram

NOTE : **in The transformer phasor diagram, The load voltage is used as a reference because quite often it is a known quantity**



Approximate Equivalent Circuits of Single-Phase Transformer

In well-designed transformer

$1 - R_1 \downarrow$ and $R_2 \downarrow$ and $X_1 \downarrow$ and $X_2 \downarrow$ and $Core$ $loss$ are $kept$ as low as $possible$

$2 - The$ low $core$ $loss$ $\downarrow \rightarrow$ $High$ $core$ $resistance$ $R_c \uparrow$

$3 - the$ $high$ $premeability$ $(\mu \uparrow)$ $ensures$ $X_m \uparrow$

SO

- The high impedance of the parallel insures low **excitation current**
- it can he assumed that. the voltage drop over the parallel branch is the same as the applied voltage

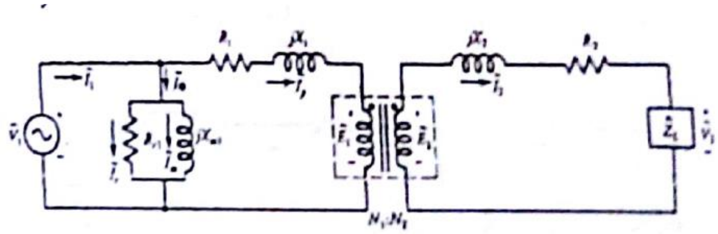
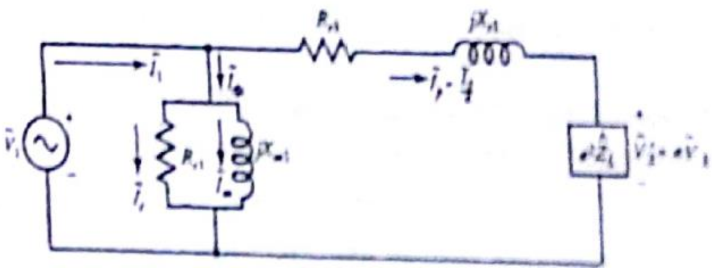
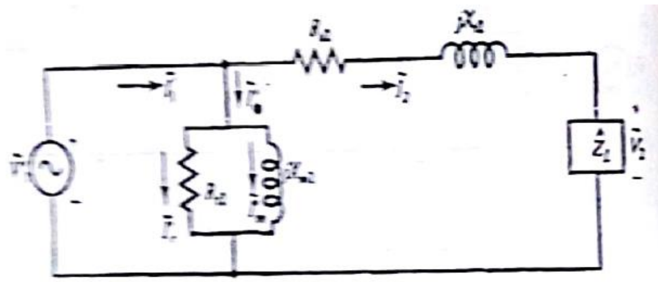


Fig. 2.13. An approximate equivalent circuit of a transformer embodying an ideal transformer.



$$Z_{e1} = R_{e1} + jX_{e1}$$
$$R_{e1} = R_1 + a^2R_2$$
$$X_{e1} = X_1 + a^2X_2$$

Aprrox. Referred to primary circuit



$$Z_{e2} = R_{e2} + jX_{e2}$$
$$R_{e2} = R_2 + R_1/a^2$$
$$X_{e2} = X_2 + X_1/a^2$$
$$R_{c2} = R_c/a^2$$
$$X_{m2} = X_m/a^2$$

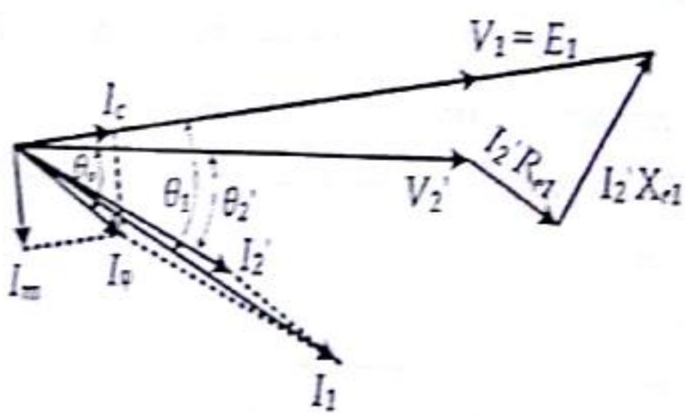
In Power Systems

Neglect the excitation current the transformer is represented as a R and L or only L

If load current increases

1- The secondary winding current increases
2- The current supplied by source increases
3- The voltage drops across the primary winding impedance increases
4- The induces emfs drops
5- Finally, the mutual flux decreases owing to the decrease in the magnetizing current
- In well-designed that decrease in flux is only from 1% to 3% so we will assume it remains the same

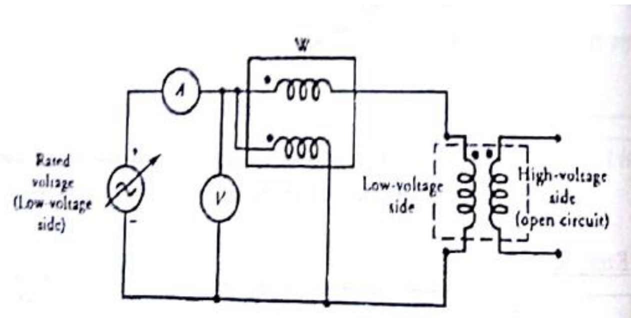
Phasor Diagram



Transformer Equivalent Circuit Parameters

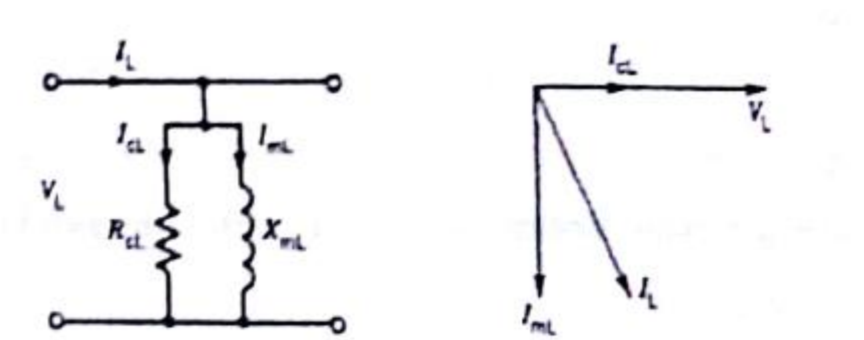
Open-Circuit Test

On low voltage (safer – available)



We get three readings

$$1 - V_{oc} = V_L^r$$
$$2 - I_{oc} = I_\phi \ (\,Excitation)$$
$$3 - P_{oc} = P_c \quad (\,no - load\ or\ core - loss\ power)$$



we also can get

$$4 - PF = \cos\phi_{oc} = \frac{P_{oc}}{V_{oc} * I_{oc}}$$
$$\phi_{oc} = \cos^{-1}\left(\frac{P_{oc}}{V_{oc} * I_{oc}}\right)$$

so we deduce

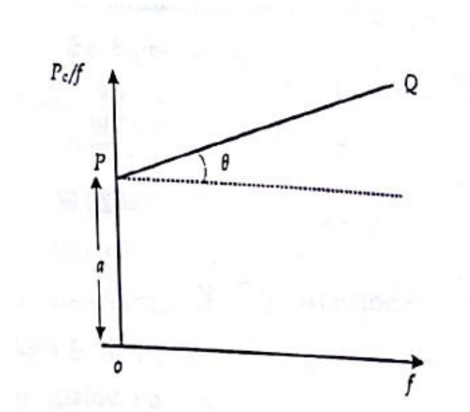
$$I_{cLV} = I_{oc}\cos\phi_{oc} \quad ; I_{mLV} = I_{oc}\sin\phi$$

$$so\ R_{cLV} = \frac{V_{oc}}{I_{cLV}} = \frac{V_{oc}^2}{P_{oc}}$$
$$X_{mLV} = \frac{V_{oc}}{I_m LV}$$

Determination of eddy current loss and hysteresis loss in transformer

$$P_h = hysteresis\ loss \propto (B_m)^{1.6}\, f$$

$$P_e = eddy\ current\ loss \propto (B_m)^2 f^2$$
$$P_c = core\ loss = P_h + P_e = af + bf^2$$
$$\therefore \frac{P_c}{f} = a + b\, f$$



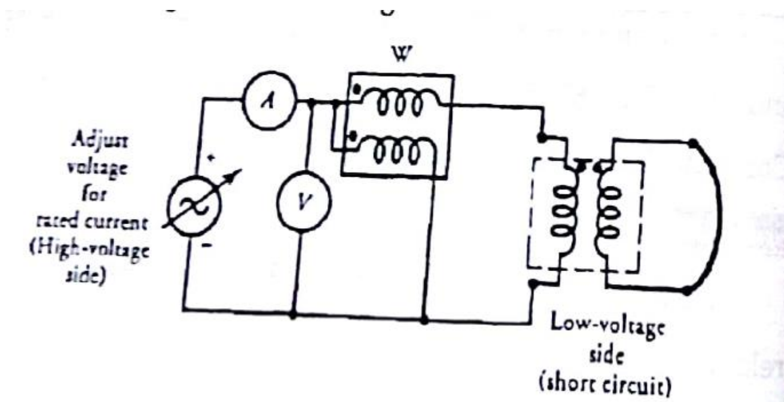
We plot , so from the plot

We measure $\boldsymbol{a}$ and $\boldsymbol{b = tan\theta}$

Then we can get the $P_h\ and\ P_e\ at\ any\ f_r\ as\ P_h = af_r\ and\ P_e = bf_r^2$

Eddy current is minimized by using thinner laminations

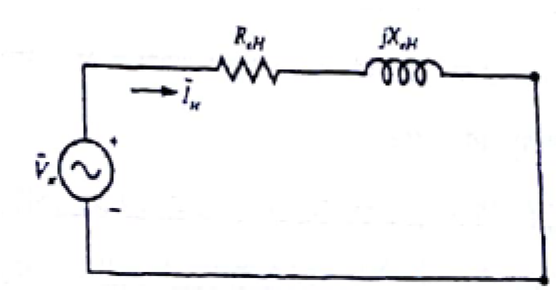
Short-Circuit Test



We measure from H.V and short the L.V.

Since voltage is very small we neglect $R_c\ and\ X_m$

$$we\ read$$
$$1 - V_{sc} = 10{:}\,15\%\ of\ rated\ voltage$$
$$2 - I_{sc} = I_H\ (rated\ current)$$
$$3 - P_{sc} = P_{cu}\ (\,full\ load\ copper\ losses)$$



$$R_{eHV} = \frac{P_{sc}}{I_{sc}^2} \quad ; \quad Z_{eHV} = \frac{V_{sc}}{I_{sc}}$$

$$X_{eH} = \sqrt{(Z_{ehv})^2 - (R_{eHV})^2}$$

For optimum design the $P_{cu}HV = P_{cu}LV$

$$so\ R_H = 0.5\ R_{eH}\ ; X_H = 0.5\ X_{eH}$$

Advantage of Transformer Tests

1- The power required to do these test is **very small** compared to full-load
for Open-Circuit P=P iron and for Short-Circuit P=P copper loss
2- Enables us to determine the **Efficiency** of the transformer at any load and PF without actually loading it
3- Short-circuit test determines $R_{e1} and\ X_{e1}$ so we can find total voltage drop referred to primary or secondary thus calculate the **voltage regulation of the transformer**

Why Transformer Rating in kVA

Important factor in design and operation of machines

- The life of insulation
- Operating temperature

So the temperature rise resulting from the losses is a determining factor in the rating of a machine

Since the
copper loss dependes on current

Iron loss depends on voltage

So

The total loss in a transformer depends on the volt-ampere product only Not on load power factor

for this reason, the rating of a transformer is in kVA not kW

Efficiency

$$\%\eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{P_{out}}{P_{out} + P_{loss}} \times 100 = \frac{V_2' I_2' \cos\phi_2}{V_2' I_2' \cos\phi_2 + P_c + {I_2'}^2\, R_{e1}} \times 100$$

As $P_c = \frac{E^2}{R_c}\ (const)$

$$\%\eta_{at\ any\ loading\ percentage} = \frac{x\, S_{out}^{FL} \cos\phi}{x S_{out}^{FL} \cos\phi\ + P_C + x^2 P_{cu}^{FL}} \times 100$$

$$x = \frac{I_2'}{{I_2'}^{FL}} = \frac{S_{out}}{S_{out}^{FL}} = \sqrt{\frac{P_c}{P_{cu}^{FL}}}\ \ at\ const\ V_2\ and\ PF$$

Maximum Efficiency

Efficiency depends on I_2' and $\cos\phi_2$

For const PF ($\cos\phi$)

$$\frac{d\eta}{dI_2'} = 0$$

$$\frac{(V_2' I_2' \cos\theta_2 + P_c + {I_2'}^2 R_{e1}) V_2' \cos\theta_2 - V_2' I_2' \cos\theta_2 (V_2' \cos\theta_2 + 2 I_2' R_{e1})}{(V_2' I_2' \cos\theta_2 + P_c + {I_2'}^2 R_{e1})^2} = 0$$

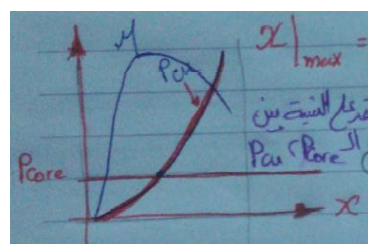
$$(V_2' I_2' \cos\theta_2 + P_c + {I_2'}^2 R_{e1}) V_2' \cos\theta_2 - V_2' I_2' \cos\theta_2 (V_2' \cos\theta_2 + 2 I_2' R_{e1}) = 0$$

$$V_2' I_2' \cos\theta_2 + P_c + {I_2'}^2 R_{e1} - I_2'(V_2' \cos\theta_2 + 2 I_2' R_{e1}) = 0$$

$$V_2' I_2' \cos\theta_2 + P_c + {I_2'}^2 R_{e1} - V_2' I_2' \cos\theta_2 - 2{I_2'}^2 R_{e1} = 0$$

$$P_c = {I_2'}^2 R_{e1}$$

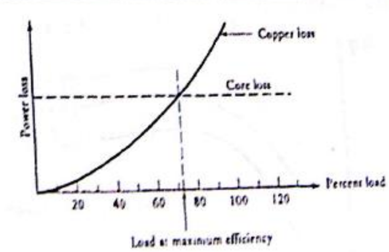
$$\boldsymbol{P_{cu} = I_2'^2\, R_{e1} = P_c \rightarrow condition\ (1)}$$



$$for\ different\ loading\ condition\ \boldsymbol{x^2 P_{cu}^{FL}} = \boldsymbol{P_c}$$

$$[\boldsymbol{x}]_{\eta Max} = \sqrt{\frac{\boldsymbol{P_c}}{\boldsymbol{P_{cu}^{FL}}}}$$

$$\%\boldsymbol{\eta} = \frac{\boldsymbol{x_{\eta_{max}}\, S_{out}^{FL}\, cos\phi}}{\left(\boldsymbol{x_{\eta_{max}}\, S_{out}^{FL}\, cos\phi}\right) + \boldsymbol{2P_c}}$$



Transformer operates at its maximum efficiency when the copper-loss curve intersects the core-loss curve, as depicted

For const load current ($I_2'^2$)

$$\frac{d\eta}{d\theta_2} = 0$$

$$\frac{-(V_2'I_2'\cos\theta_2 + P_c + I_2'^2R_{e1})V_2'I_2'\sin\theta_2 + (V_2'I_2')^2\cos\theta_2\sin\theta_2}{(V_2'I_2'\cos\theta_2 + P_c + I_2'^2R_{e1})^2} = 0$$

$$-(V_2'I_2'\cos\theta_2 + P_c + I_2'^2R_{e1})V_2'I_2'\sin\theta_2 + (V_2'I_2')^2\cos\theta_2\sin\theta_2 = 0$$

$$V_2'I_2'\sin\theta_2\left(-V_2'I_2'\cos\theta_2 - P_c - I_2'^2R_{e1} + V_2'I_2'\cos\theta_2\right) = 0$$

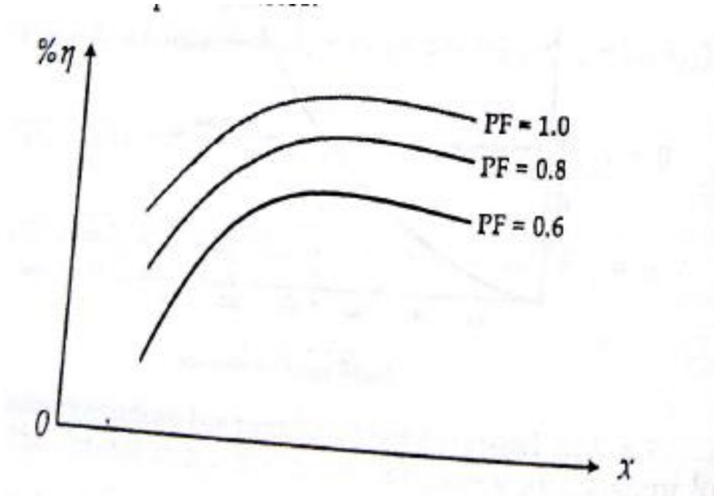
$$-V_2'I_2'\sin\theta_2\left(P_c + I_2'^2R_{e1}\right) = 0$$

$$V_2'I_2'\sin\theta_2 = 0$$

Therefore, the condition for maximum efficiency in this case is

$$\sin\theta_2 = 0 \xrightarrow{yields} \theta_2 = 0$$

$$\cos\theta_2 = 1$$



So the max max efficiency is when (1) PF =1 AND (2) $P_c = P_{cu}$

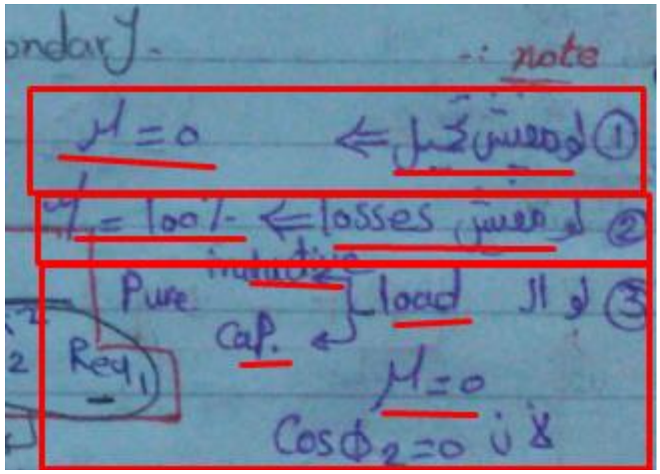
ALL-DAY Efficiency

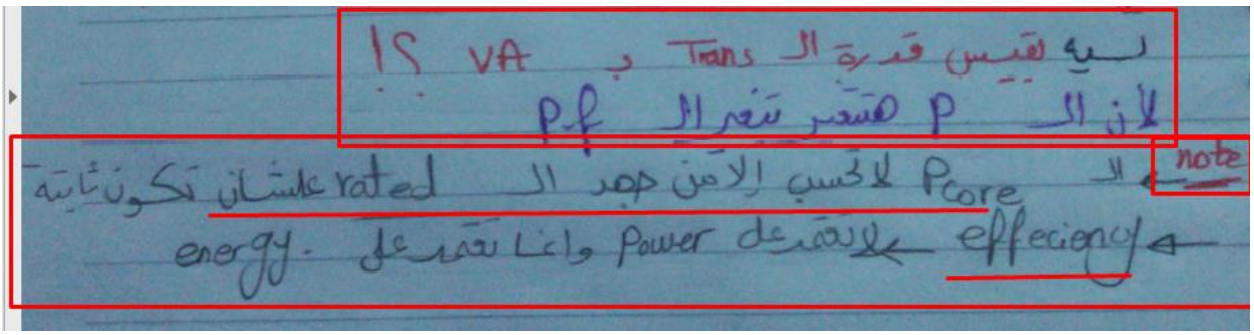
Power Transformer : Designed for maximum efficiency occurring near the rated output

Distribution Transformer : Designed for maximum efficiency occurring at the average output power

$$\eta_{AD} = ALL - DAY\ or\ ENERGY\ efficeincy$$

$$\eta_{AD} = \frac{E_{out}}{E_{out} + E_{loss}} = \frac{\sum x * S * PF * t}{\sum x * S * PF * t + 24 \times P_c + \sum x^2 P_{cu}.t}$$





Voltage Regulation

Because a constant output voltage is important and it changes <u>due to series impedence</u>

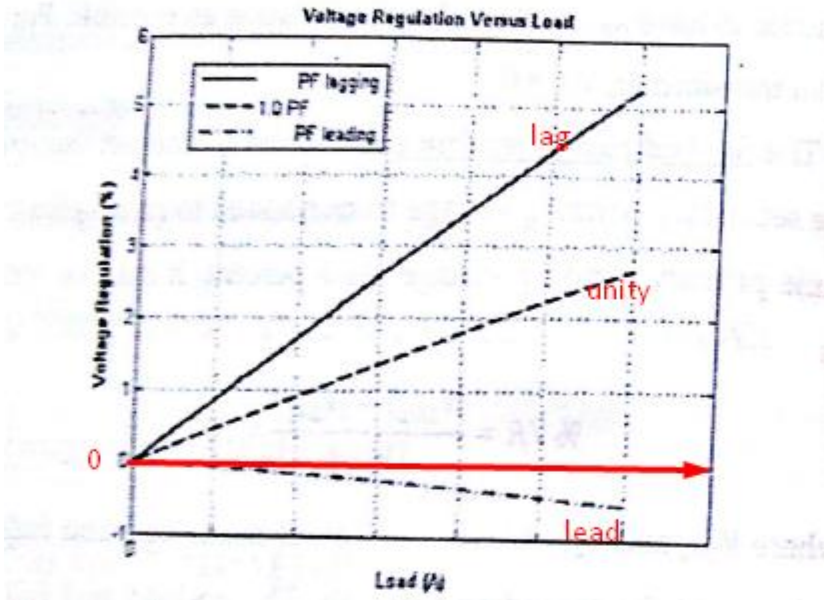
We define best VR = 0

<u>The full-load voltage regulation</u> : the net change in the secondary winding voltage from no-load to full-load for the same primary winding voltage.

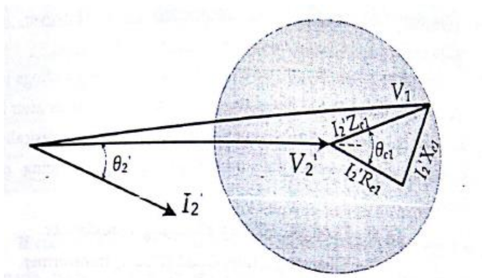
$$\%VR = \frac{V_{2NL} - V_{2FL}}{V_{2FL}} \times 100 = \frac{V_1 - aV_2}{aV_2} \times 100$$

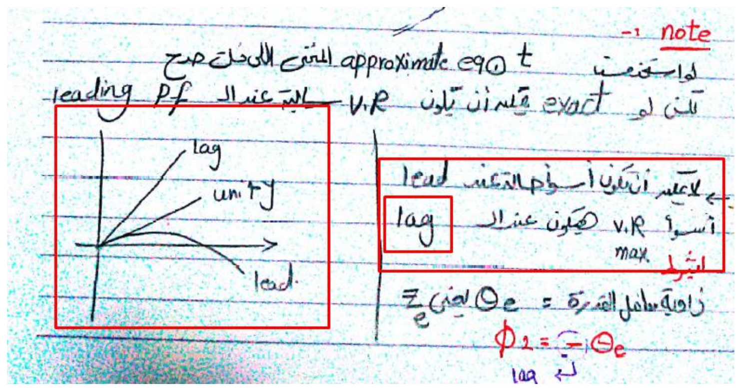
Because $V_1 = V_2' \angle 0 + I_2 \angle \phi_2 \times Z_{e1} \angle \theta_{e1}$ It dependes on

1- Load current I_2'
2- Power Factor $\cos \phi_2$



Maximum Voltage Regulation





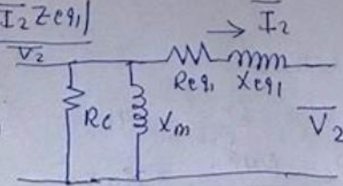
For this phasor diagram we note :

$$V_1 \text{ is Max if } I_2'Z \text{ in phase with } V_2'$$

$$so\ VR_{MAX}\ at\ \boldsymbol{\phi_2} = -\boldsymbol{\theta_{e1}}$$

Prove : $\%VR_{max} = \dfrac{|I_2{'}Z_{e1}|}{|V_2'|_{rated}} \times 100$

Prove that $V_R|_{max} = \frac{|\bar{I}_2 Z_{eq_1}|}{\bar{V}_2}$



$\because V_R = \frac{|V_1| - |\bar{V}_2|}{|\bar{V}_2|}$, since $|\bar{V}_2|$ is Kept constant

so $V_R \to max$, when $|V_1| - |\bar{V}_2| \,]_{max} \to |V_1|_{max}$

since $V_1 = \bar{V}_2 + \bar{I}_2 * Z_{eq_1}$

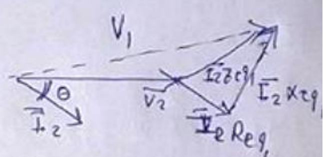
∵ The Algebric sum of value is higher than the vector sum.

then $\bar{V}_2$ and $(\bar{I}_2 Z_{eq})$ must be inphase

since $\bar{V}_2$ is the reference

so $Arg[\bar{I}_2 Z_{eq_1}] = 0$

so $Arg[\bar{I}_2] = -Arg[Z_{eq_1}]$



∴ $\theta_2 = -\theta_{eq_1}$

so $|V_1|_{max}| = |\bar{V}_2| + |\bar{I}_2 Z_{eq_1}|$

so $V_R\% = \frac{|\bar{V}_2| + |\bar{I}_2 Z_{eq_1}| - |\bar{V}_2|}{|\bar{V}_2|} = \frac{|\bar{I}_2 Z_{eq_1}|}{|\bar{V}_2|}$

Transformer taps and voltage regulator

No-Load (off-circuit / de-energized) Tap-changing Transformer (NLTC)

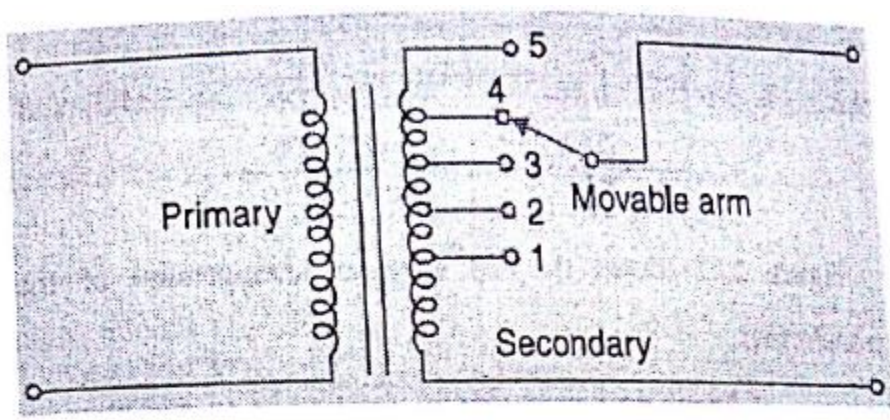


Fig. 2.26. Tap changing at no-load transformer.

Taps can be on low to change the output voltage and change turns ratio preferred on high voltage side for less current in the device

Disadvantage

Can’t be used on load

1- Break then Make : it will cause arcing and break in the circuit

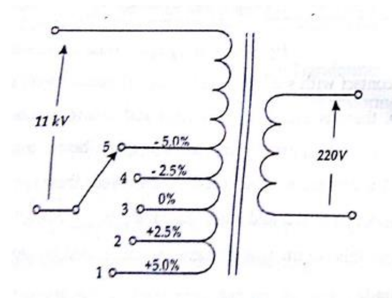
2-Make before Break : the coils will be short-circuited and carry damaging heavy current

EXAMPLE

Mostly it’s (4 taps at 10% 2.5% each) or (2 taps at 10% 5% each)

For 100-kVA, 11,000/ 220-V

Taps	Rated Voltages
+5.0%	11,550/220
+2.5%	11,275/220
0.0%	11,000/220
-2.5%	10,725/220
-5.0%	10,450/220



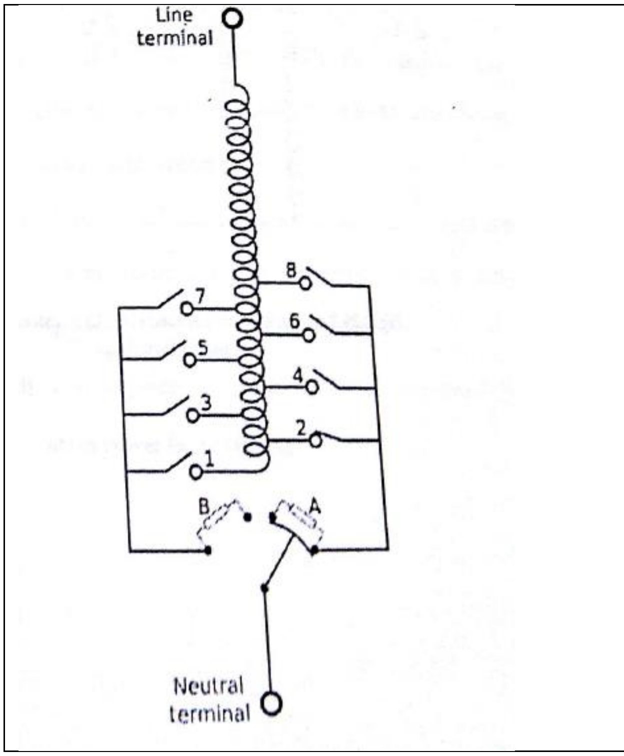
automatic
meter
A m r → reading

Tap-Changing Under Load Transformer (TCUL)

-Contains **a built-in voltage sensing circuit** that automatically changes taps to keep the voltage constant

Classified :

1- Changing by impedance or reactor transition	2-Changing using equal parallel windings.



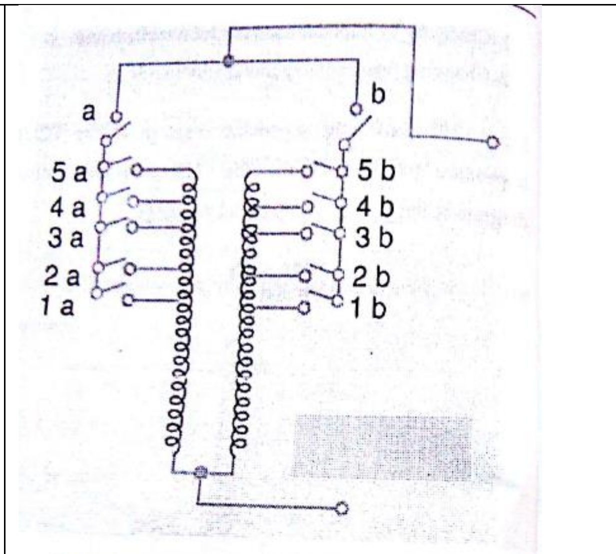


Fig. 2.29. Tap changing under load (TCUL) transformer using parallel windings

Per-Unit System

$$p.u\ value = \frac{actual\ value}{base\ value}$$

$$we\ select\ V_b\ \&\ S_b\ and\ deduce\ \ I_b = \frac{S_b}{V_b}\ \ , Z_b = \frac{V_b}{I_b} = \frac{V_b^2}{S_b}$$

Q: Prove that the per-unit transformer voltage, current and impedence is the same referred to either side of the transformer.

Transformer Equivalent Circuit in P.U

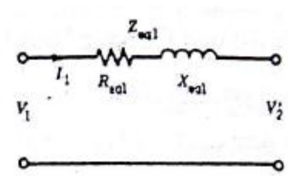
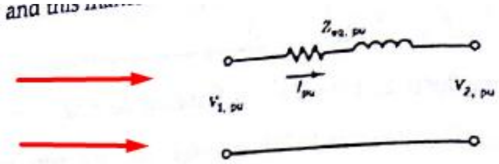


Fig. 2.30. Transformer equivalent circuit in actual values.



NOTE : the per-unit transformer voltage, current and impedence is the same referred to either side of the transformer.

Full-Load Copper Loss in P.U.

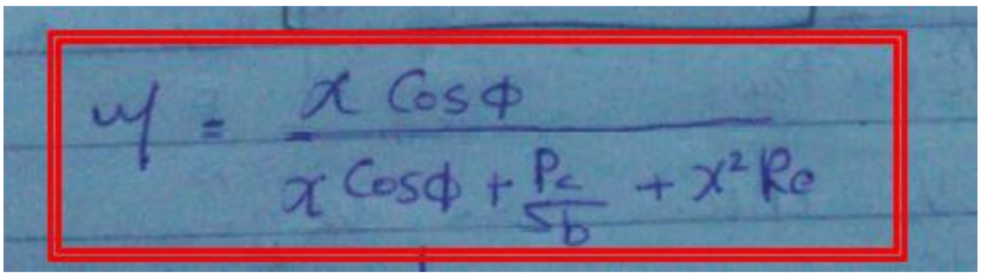
$$P_{cu}^{FL} = I_{1.FL}^2 R_{e1}$$

$$[P_{cu}^{FL}]_{pu} = \frac{I_{1.FL}^2 * R_{e1}}{S_b} = \frac{I_{1.FL}^2 * R_{e1}}{V_b I_b}$$

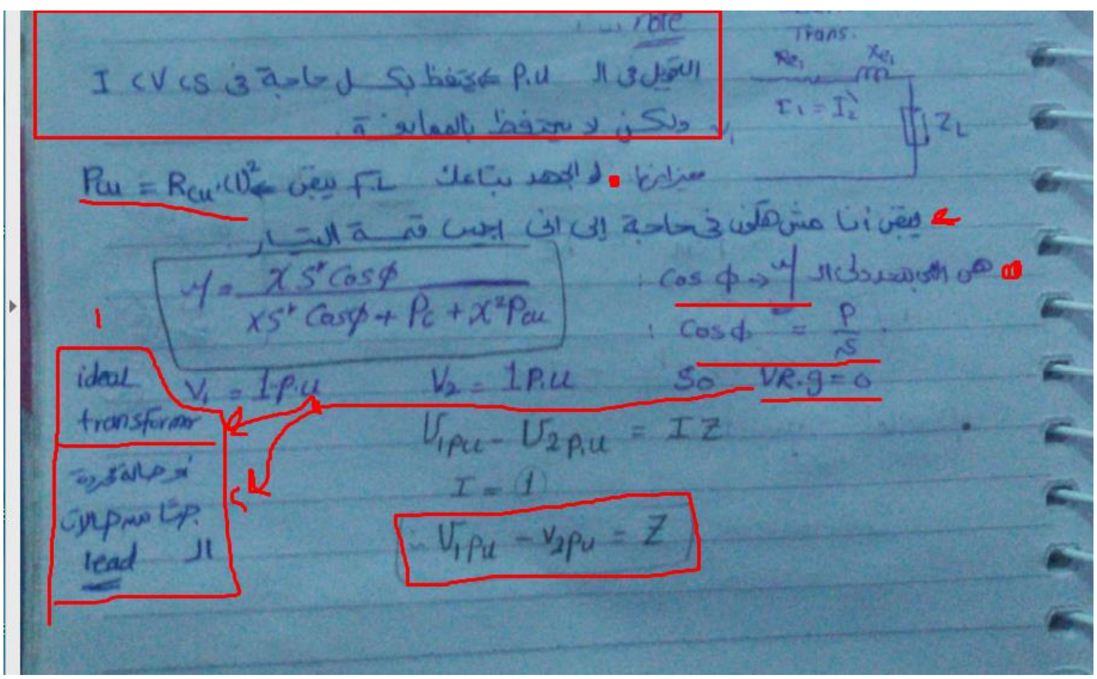
$$since \;\; I_{b1} = I_{1,FL}$$

$$Z_{b1} = \frac{V_{b1}}{I_{b1}}$$

$$\therefore \;\; [P_{cu}^{FL}]_{pu} = R_{e1_{pu}}$$



Hence, the fullload copper loss in per-unit system equal the transformer resistance expressed in per unit value of the resistance is therefore more useful than its actual value in determining the performance of the transformer

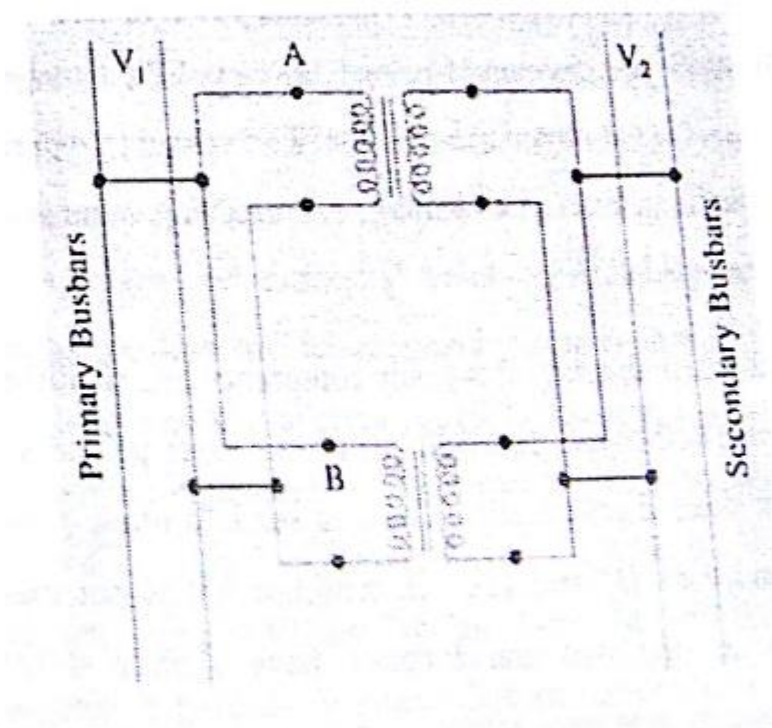


الـ distribution Transformer { يتم تصميمه بحيث η_{max} تحصل عند 50% من الـ load

• لو التبريد بتاعها هوا ممكن توصل لـ 80%

• لو التبريد بتاعها زيت " " لـ 100%

Parallel Operation of Single Phase Transformer



in order to

- avoid any local circulating currents and to ensure that

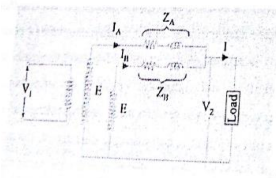
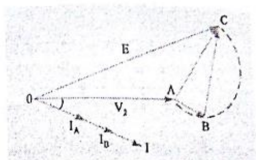
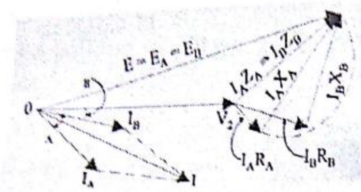
-the transformers share the common load in proportion to their kVA ratings.

The conditions are:

1	**Primary windings of the transformers should be suitable for the supply system <u>voltage and frequency.</u>**
2	**The transformers should be properly connected With**

	regard to polarity
3	**The voltage ratings of both- primaries and secondaries. should be identical. In other words, the transformers should have the same turn ratio i.e. transformation ratio.** **IF NOT SATISFIED (i.e having slightly different turn ratio)** There will be difference in induced emfs so, in no load : slight circulating current between each s and p windings In loaded : unequal loading conditions Hence, we **can't take full kVA** output of the parallel-connected or it will overheat
4	**To avoid -circulating current – operating at different PFs** **1- The Percentage impedance should be equal in magnitude 2- have the same X/R ratio** **IF NOT SATISFIED (impedance triangles are not identical in shape and size)** -the power factors at which the two transformers operate will be different from the power factor of the common load -the two transformers will not share the load in proportion to their kV A ratings.
5	**To avoid -circulating current** **With transformers having different kVA ratings, The equivalent impedances should be inversely proportional to the individual kVA rating**
6	**For parallel operation, the regulation must be the same** $$\boldsymbol{it\ meas\ that\ \ Current \propto Ratings \propto \frac{1}{Numerical\ Impedances}}$$ $$\boldsymbol{their\ Percentage\ impdences\ are\ identical \frac{X_1}{R_1} = \frac{X_2}{R_2}}$$ **IF NOT X/R identical** divergence of phase angle of the two currents, With the result that one transformer will be operating with a higher and the other with a lower power factor than that of the combined load.

Two Cases

Case (1) Ideal Case	Case (2) Equal Voltage Ratios
  $I = I_A + I_B$ $V_2 = E - I_A Z_A$ $V_2 = E - I_B Z_B$ $V_2 = E - I Z_{AB}$ $I_A Z_A = I_B Z_B$ $\frac{I_A}{I_B} = \frac{Z_B}{Z_A}$ $\therefore I_A = I\frac{Z_B}{Z_A + Z_B}$ & $I_B = I\frac{Z_A}{Z_A + Z_B}$	$E_A = E_B = E$ would be true if the magnetizing currents of the two transformers are not much different from each other Unequal Voltage Impedance Ratio  $\therefore I_A = I\frac{Z_B}{Z_A + Z_B}$ & $I_B = I\frac{Z_A}{Z_A + Z_B}$

Report:-

Let $E_A > E_B$

ارسم الـ P.D للحالة دي.

$\frac{X}{R} = \frac{3}{4}$ ، $\frac{X}{R} = \frac{6}{8}$

3. Case (2)

• هيبقى اقل فى الـ Power losses

$\frac{I_A}{I_B} = \frac{Z_A}{Z_B}$

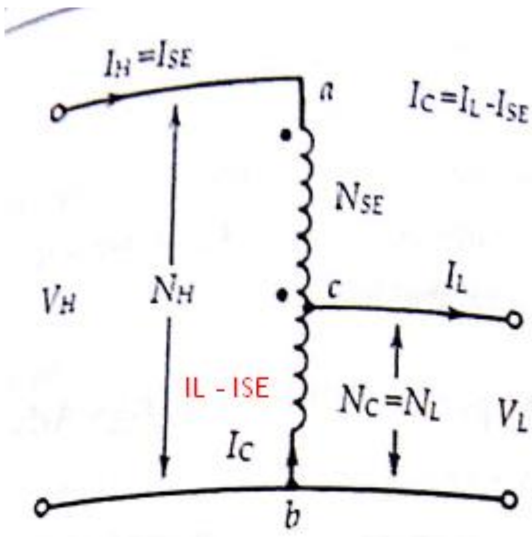
if $I_A = 10A$, $Z_A = 6 + J8$; $I_B = 10A$, $Z_B = 8 + J6$

ارسم الـ phasor لهم

مهم تفريق معامل القدرة

CH 3 : Autotransformers

- Energy is transferred from primary to secondary
  through **conduction(electric connection) & Induction (Magnetic Coupling)**
- The closer the voltages of Primary and secondary are , The greater the power advantage.
- It also can be used as a variable transformer



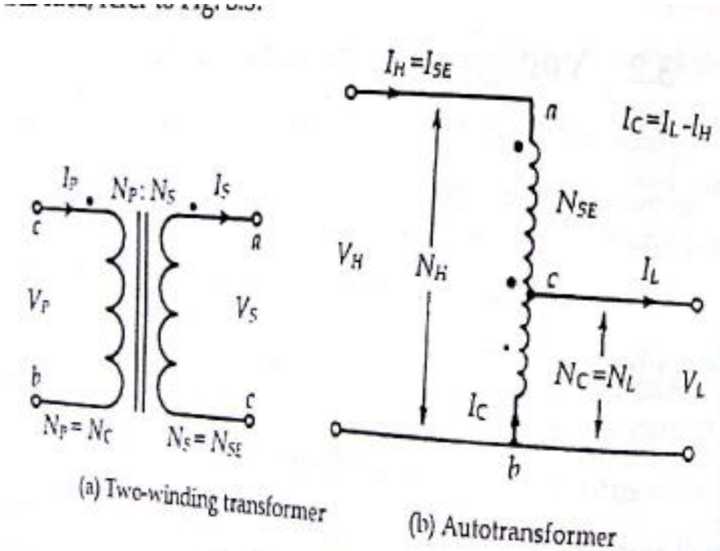
$$N_H = N_{SE} + N_C$$
$$V_L = V_C$$
$$V_H = V_C + V_{SE}$$
$$I_H = I_{SE}$$
$$I_L = I_C + I_{SE}$$

Voltage and Current Relationships

Voltage	Current
$\boxed{\frac{V_H}{V_L} = \frac{N_H}{N_L} = \frac{N_{SE} + N_C}{N_C}}$	Net Mmf=0 $N_{SE} I_H - N_C (I_L - I_H) = 0$ $N_{SE} I_H - N_C I_L + N_C I_H = 0$ $(N_{SE} + N_C) I_H = N_C I_L$ $\boxed{\frac{I_H}{I_L} = \frac{N_C}{N_{SE} + N_C} = \frac{N_L}{N_H}}$

Apparent Power Advantage

if a conventional two-winding transformer is reconnected as an autotransformer; it can handle much more power than it was originally rated for.



(a) Two-winding transformer (b) Autotransformer

Fig. 3.3. Single-phase autotransformer

$$S_{out} = V_L I_L \qquad S_{in} = V_H I_H$$
$$S_{in} = S_{out} = S_{IO}$$

$$S_W = S_{ac} = I_H(V_H - V_L) = V_H I_H \left(1 - \frac{V_L}{V_H}\right) = V_H I_H \left(1 - \frac{N_L}{N_H}\right)$$

$$S_W = S_{bd} = V_L(I_L - I_H) = V_L I_L \left(1 - \frac{I_H}{I_L}\right) = V_L I_L \left(1 - \frac{N_L}{N_H}\right)$$

$$S_W = S_{IO} \frac{(N_H - N_L)}{N_H}$$
$$\frac{S_{IO}}{S_W} = \frac{N_{SE} + N_C}{N_{SE}} > 1$$

Conclusion : The Apparent power rating advantage of an autotransformer over a conventional two winding transformer

Saving in copper in autotransformer

$$\boldsymbol{weight \propto NI \ \rightarrow \ say\ W = NI}$$

$$(N_H - N_L)I_H$$

$$N_L(I_L - I_H)$$

$$total\ weight\ W_{auto} = (N_H - N_L)I_H + N_L(I_L - I_H)$$

$$weight\ for\ W_{2w} = N_H I_H + N_L I_L$$

$$\frac{W_{auto}}{W_{2W}} = \frac{(N_H - N_L)I_H + N_L(I_L - I_H)}{N_H I_H + N_L I_L}$$

$$\frac{W_{auto}}{W_{2W}} = \frac{N_H I_H - N_L I_H + N_L I_L - N_L I_H}{N_H I_H + N_L I_L} = \frac{N_H I_H + N_L I_L - 2N_L I_H}{N_H I_H + N_L I_L} = 1 - \frac{2N_L I_H}{N_H I_H + N_L I_L}$$

$$(\ divide\ N_H I_H)$$

$$= 1 - \frac{2\frac{I_H}{I_L}}{1 + \frac{N_H}{N_L} \times \frac{I_H}{I_L}} = 1 - \frac{2\frac{N_L}{N_H}}{1 + \frac{N_H}{N_L} \times \frac{N_L}{N_H}} = 1 - \frac{N_L}{N_H} = \frac{N_H - N_L}{N_H} < 1$$

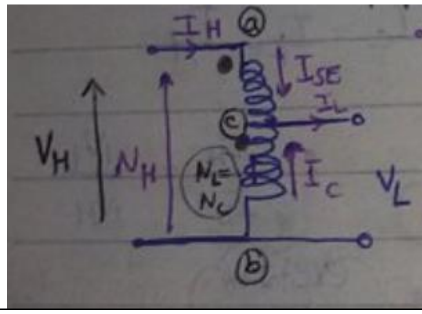
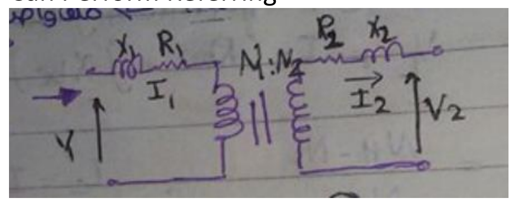
$$W_{auto} = \left(1 - \frac{1}{a}\right) W_{2W}$$

$$\therefore\ \ |saving\ in\ copper| = \ W_{auto} - W_{2W} = \frac{1}{a} W_{2W}$$

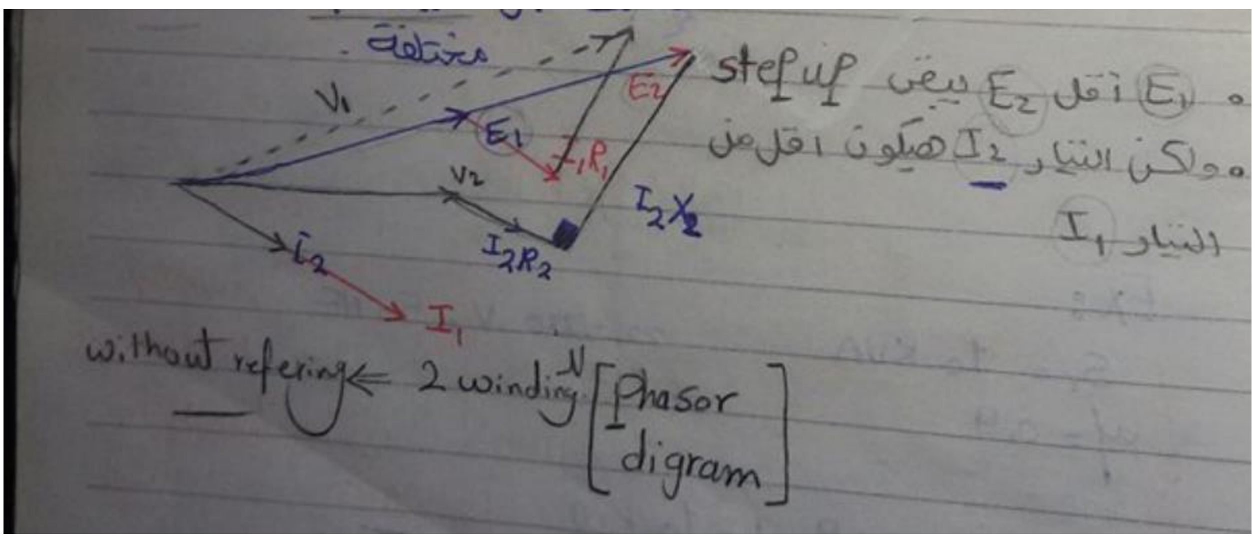
Note : the saving in copper weight in auto transformer is **inversely propotional to turns ration conventional two winding transformer.**

Advantage and disadvantage

Advantage	Disadvantage
1. **Variable output voltage** when a sliding contact is used for the secondary. 2. **Increased kVA** rating $\boldsymbol{S_{IO}} > \boldsymbol{S_W}$, 3. **Saving weight of copper**, (an autotransformer requires less copper than a two-winding transformer of similar rating), therefore, an autotransformer has smaller size than a two-winding transformer of the same rating. 4. **Lower leakage reactance and lower losses** therefore an autotransformer operates at a higher efficiency than a two-winding transformer of similar rating. 5.has a **better voltage regulation** than a two-winding one of the same rating 6. Stabilizer	1.direct connection between the primary and secondary sides (no electrical insulation) 2. The short-circuit current is much larger than for the two-winding transformer of the same rating. Short circuit for secondary causes part of primary to be short-circuited as well. 3. Used only for small turns ratio 4. Mechanical issue (can cause firing because of arcing)

Auto	2 winding
- Magnetic and electric connection(induction and conduction). - 1 Windings - Can’t perform referring they are not sperate windings  -	- Magnetic Connection (induction only) - Two separate winding - Can Perform Referring  -

Phasor of 2 Winding without referering



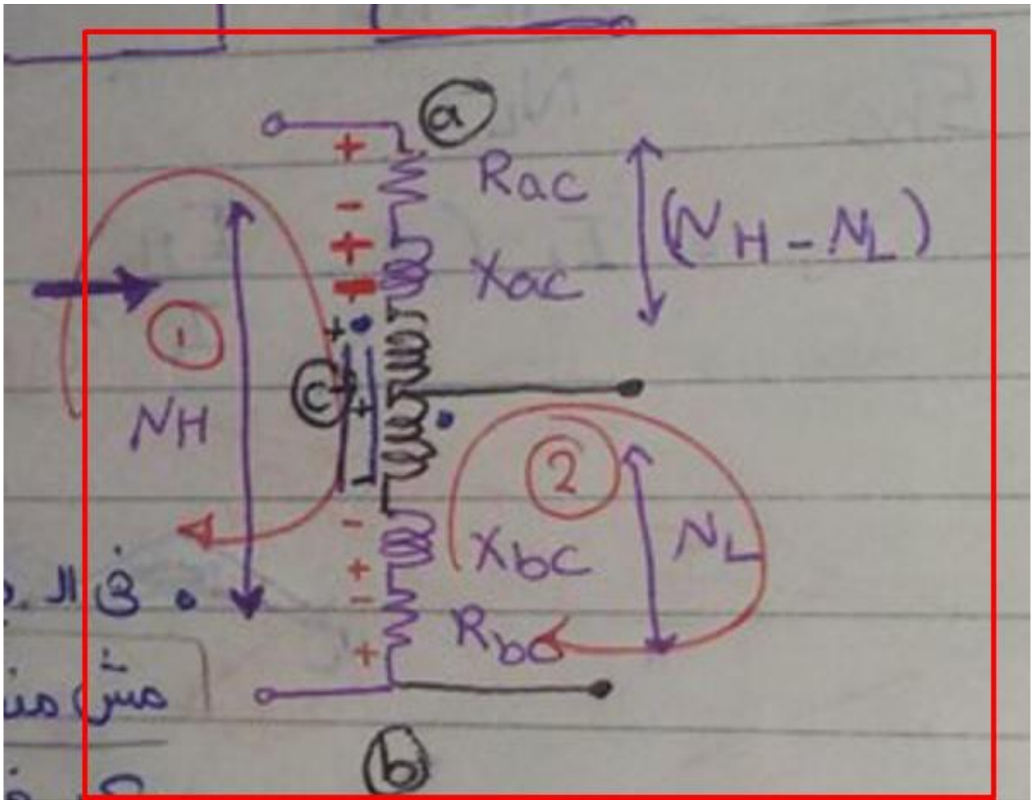
$$E_2 = V_2 + I_2R_2 + jI_2X_2$$

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} \quad , \quad \frac{I_1}{I_2} = \frac{N_2}{N_1}$$

.

.

Auto phasor



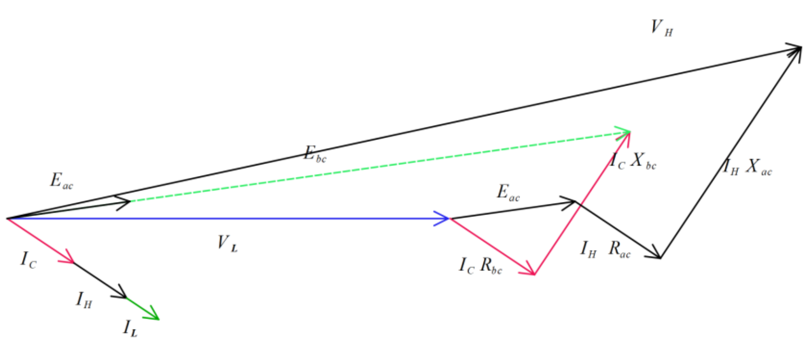
$loop\ (1)$	$loop\ (2)$
$V_H = E_{ac} + I_H(R_{ac} + jX_{ac}) + \overbrace{[E_{bc} - I_C(R_{bc} + jX_{bc})]}^{\text{V\_L}}$	$E_{bc} = V_L + I_c(R_{bc} + j\,X_{bc})$

$$\therefore V_H = V_L + E_{ac} + I_H(R_{ac} + X_{ac})$$

$$\frac{E_{ac}}{E_{bc}} = \frac{(N_H - N_L)}{N_L} \qquad ; \quad I_c = I_L - I_H = I_L\left(1 - \frac{I_H}{I_L}\right) = I_L\left(1 - \frac{N_L}{N_H}\right)$$

No excitation branch no angle between I_H & I_L

PHASOR OF AUTO TRANSFORMER

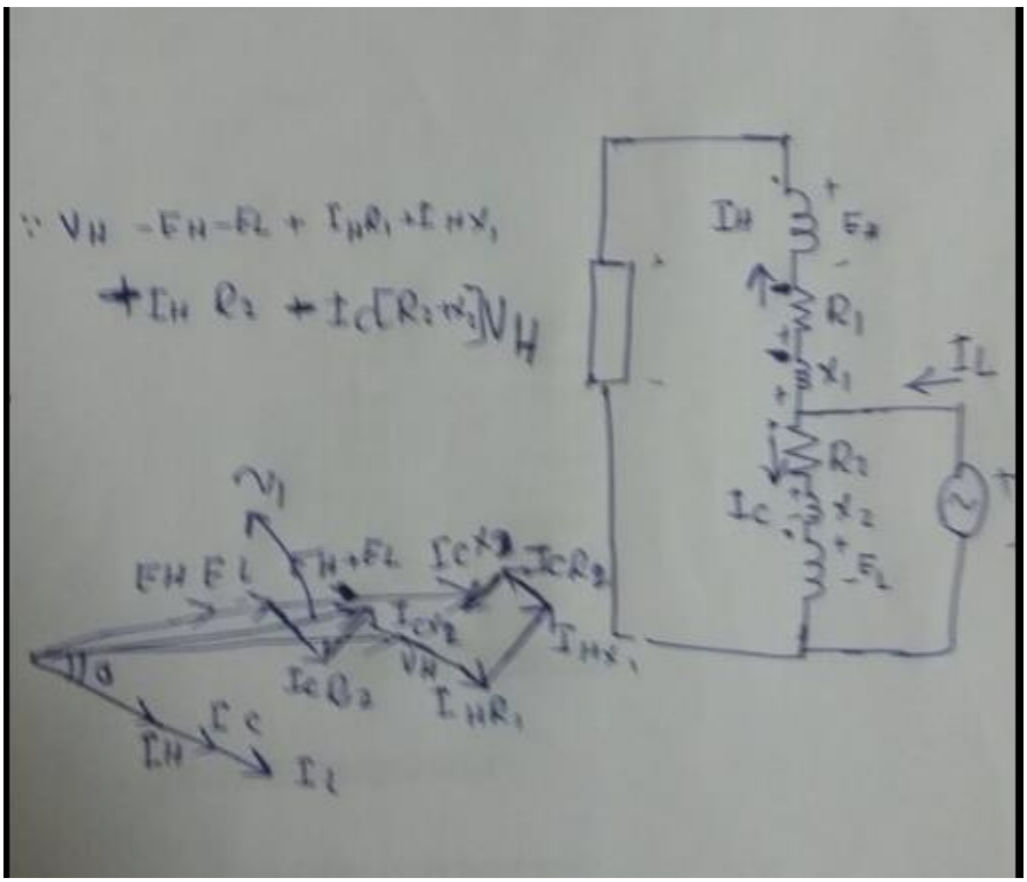


ملحوظه لو ال Load محطوط غلى ال High Voltage يبقي ال Phasor هيبدا من الVh

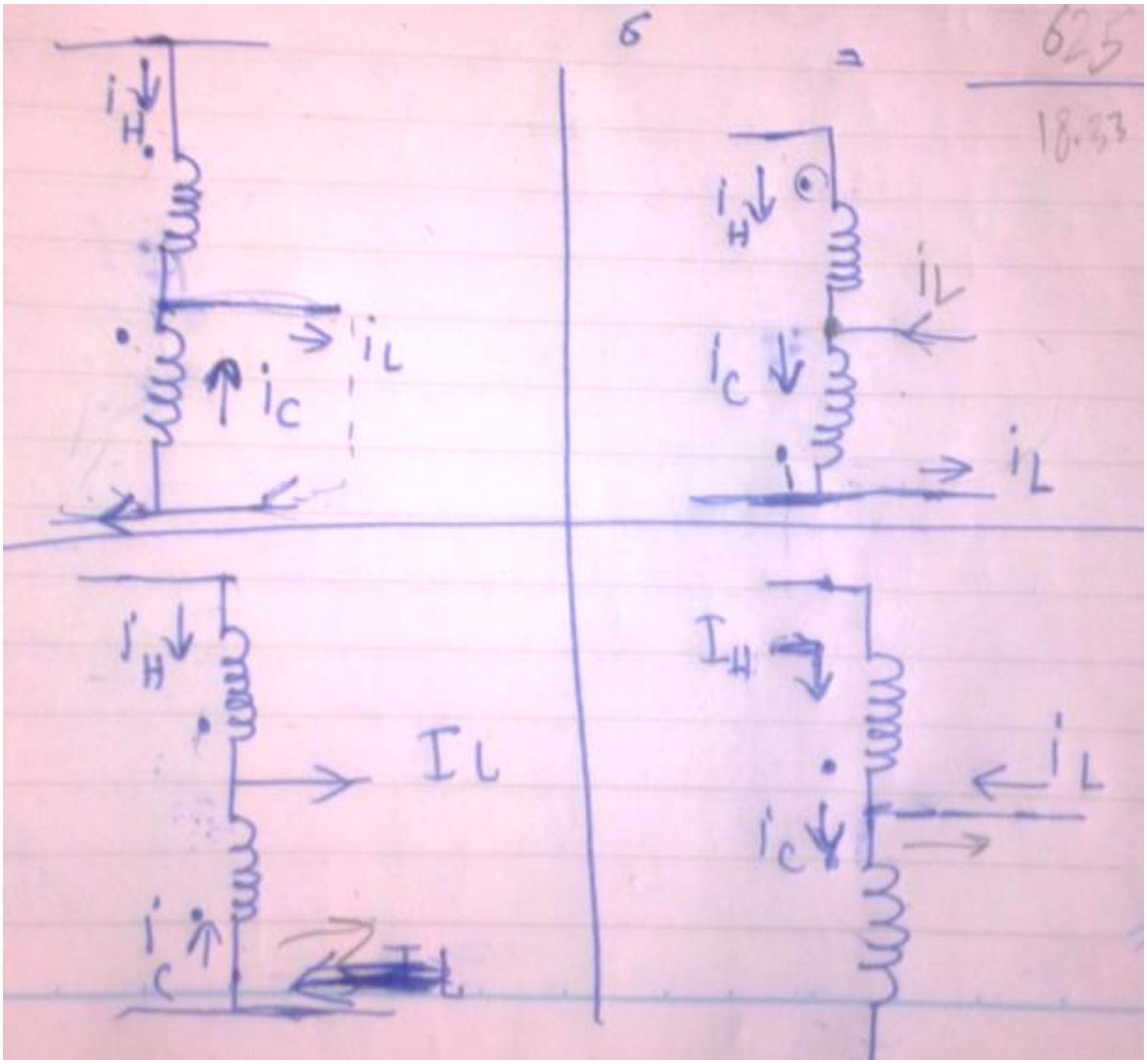
في الكفائه بين 2W و ال auto

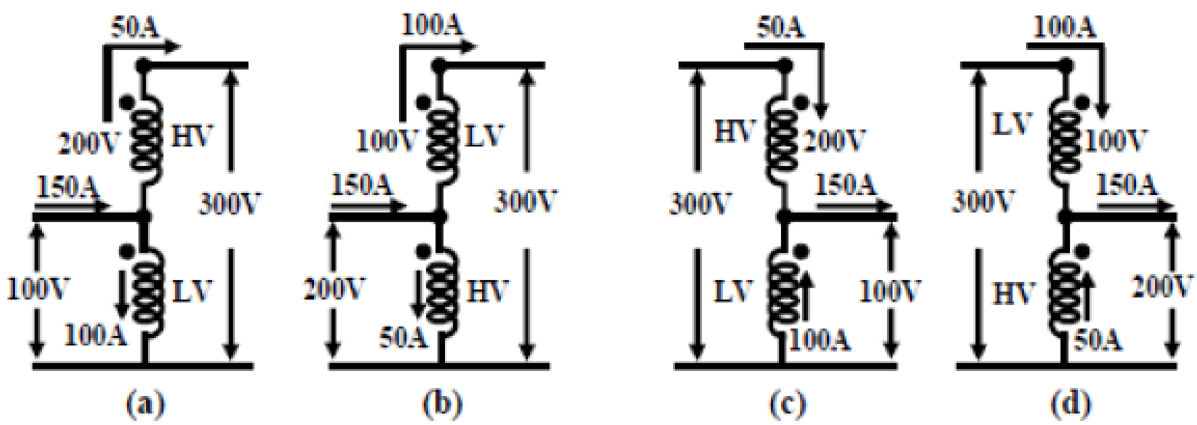
نجيب Pc ثابته لنفس الفيض
الPcu لازم الاتنين يكونو عند نفس حاله التحميل لو مش كده

$$\frac{P_{cu_{auto}}}{P_{cu_{2wind}}} = \left(\frac{I_{auto}}{I_{2W}}\right)^2$$



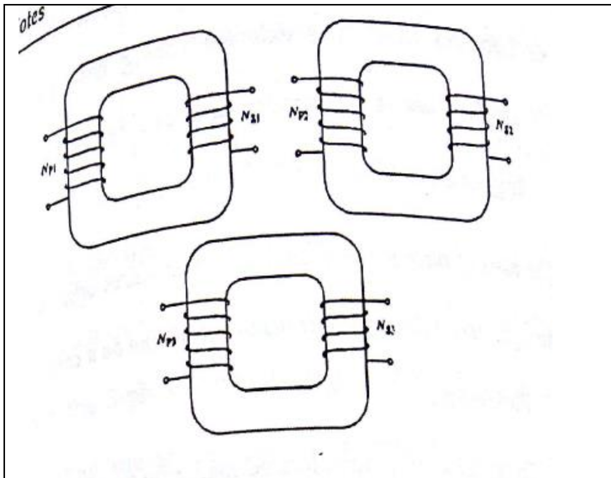
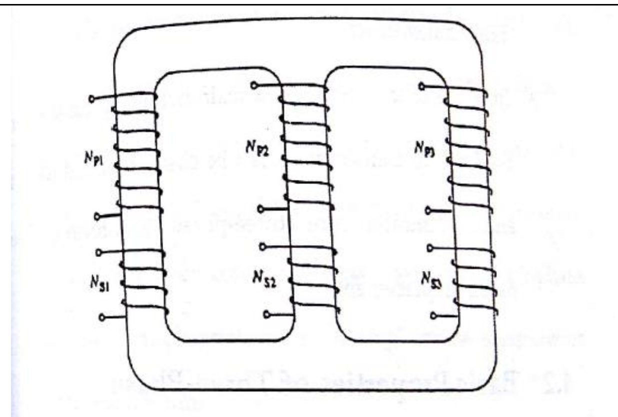
Different Configurations for transformer





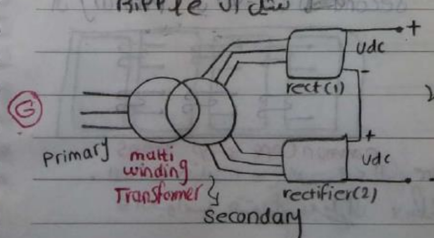
Three-Phase Transformers

- Has 3-phase windings (can be connected either Star or Delta)
- Can be (3 1- ϕ bank of XFMRs or 3- ϕ on the same magnetic core)

 Fig. 4.1. A three-phase transformer bank.	 Fig. 4.2. A three-phase transformer in a common core.
1- Flexibility 2- In case of unbalanced load,in one or more transformers in the bank can be replaced by a larger or smaller KVA rated transformer 3- In terms of maintenance, a malfunctioning transformer in the bank of transformers can be easily replaced while the entire common core three-phase transformer would require replacement 4- Can serve as a V(open delta) for a while during fault in one of the transformer	5- Lighter 6- Smaller 7- Cheaper 8- Requires much less external wiring than the bank of single phase transformers and can typically achieve a higher efficiency 9- Shell better for distribution of field

multi-winding Transformer وبسمى علشان الربط لتو صليه
بستخدم فى
High voltage DC Transmission
بعين مشامحتاج مكثفات عشان تقلل ال Ripple

* ممكن استخدام ال multi-winding



Vdc ⇒ كده حصلت عندي DC عالي وبالتالي التيار هيقل محتاجة مقطع السلك هيقل

ال shift 30° بين

application → off. shour sys. →

• لوال secondary فى 2-winding وكل winding واحده Y والتانيه Δ
هحصل ع mult-pulse (12 Phase Transformer) فال ripple هيقل
وهكذا لو 3 winding هحصل ع (18 Pulse)
← Zigzag Transformer نستخدم ال Phase-Shift Transformer بعين
علشان يظبط الزوايا.

Basic Properties of Three-Phase Transformer Bank

Transformer Banks

$$\frac{\boldsymbol{3-\phi\ input\ voltage}}{\boldsymbol{3-\phi\ output\ voltage}}\ depends\ on\ \ (1)\ a:turns\ ratio\ \ (2) how\ they\ \ are\ connected$$

$$\boldsymbol{Phase\ Shift}\ \ depends\ on\ \ (1)\ a:turns\ ratio\ \ (2) how\ they\ \ are\ connected$$

Phase shift allows us if needed to change number of phase(multi winding too)

$$from\ 3-\phi\ \ to\ (\ 2-\phi\ ,6-\phi, 12-\phi\ or\ 5-\phi\ "with\ appropriate\ choice\ of\ single\ phase\ transformers)$$

Warning : Always notice polarity to avoid (short circuit or unbalance)

$\underline{\boldsymbol{Y-Y}}$ $\frac{\mathbf{V_p}}{\mathbf{V_s}}=\mathbf{a}$	$\underline{\boldsymbol{\Delta-\Delta}}$ $\frac{\mathbf{V_p}}{\mathbf{V_s}}=\mathbf{a}$
$\underline{\boldsymbol{Y-\Delta}}$ $\frac{\mathbf{V_p}}{\mathbf{V_s}}=\mathbf{a}*\sqrt{\mathbf{3}}$	$\underline{\boldsymbol{\Delta-Y}}$ $\frac{\mathbf{V_p}}{\mathbf{V_s}}=\frac{\mathbf{a}}{\sqrt{\mathbf{3}}}$

Transformer Winding Connection Designations

Is divided to three parts

First Symbol **High Voltage** **capital Letter**	**Second Symbol** **Low Voltage** **small letters**	**Third Symbol** **Phase displacement** **(with clock hour = 30°)**
$D=Delta$ $Y(S)=Star$ $N-Neutral$ $Z=Zigzag$	$d=Delta$ $y(s)=Star$ $n=Neutral$ $z=Zigzag$	$12=0°\ or\ 360°$ $1=-30°$ $2=-60°$ $3=-90°$ $6=180°$
	$\boldsymbol{Example:Dyn11}$	
Delta	Star point conn. To neutral	$30°\ Leading$

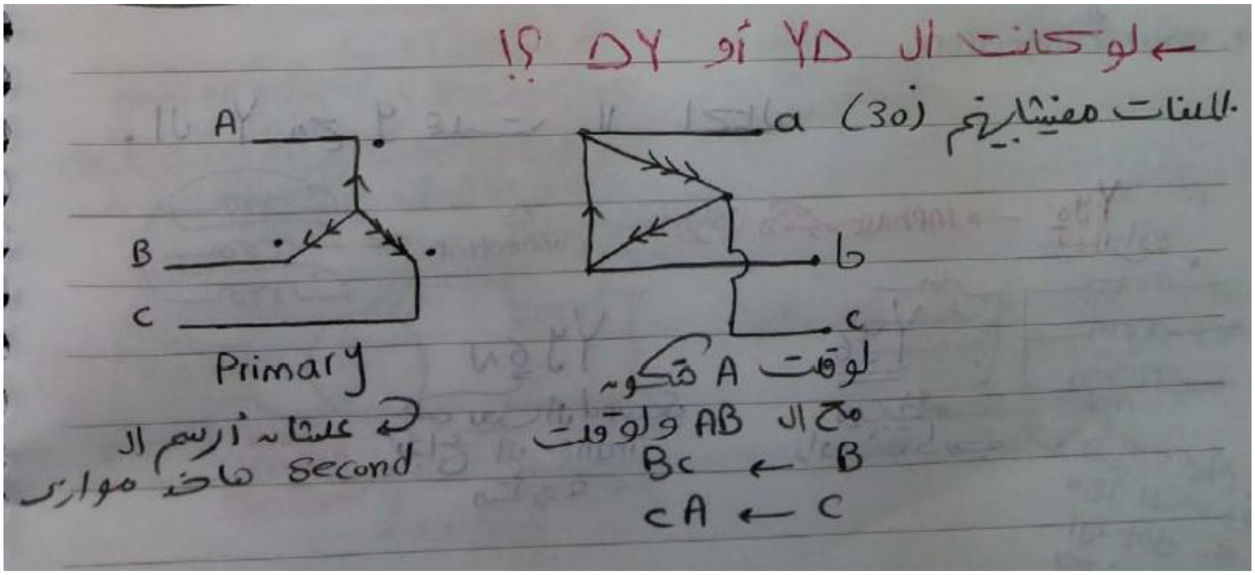
Basic Idea of Winding

As single phase transformer

According to <u>which ways round the coils are connected</u> voltages can be (in phase or anti-phase(180)) but in 3-phase transformer winding a number of option appear

1- Coil voltages can be in-phase or antiphase
2- Coils connected in star or delta
3- Star (neutral in brought out to an external terminal or not)
4- Six ways to wire star
5- Six ways to wire delta

} *Determines the phase relation between the primary and secondary windings*



SIX WAYS TO WIRE STAR AND DELTA

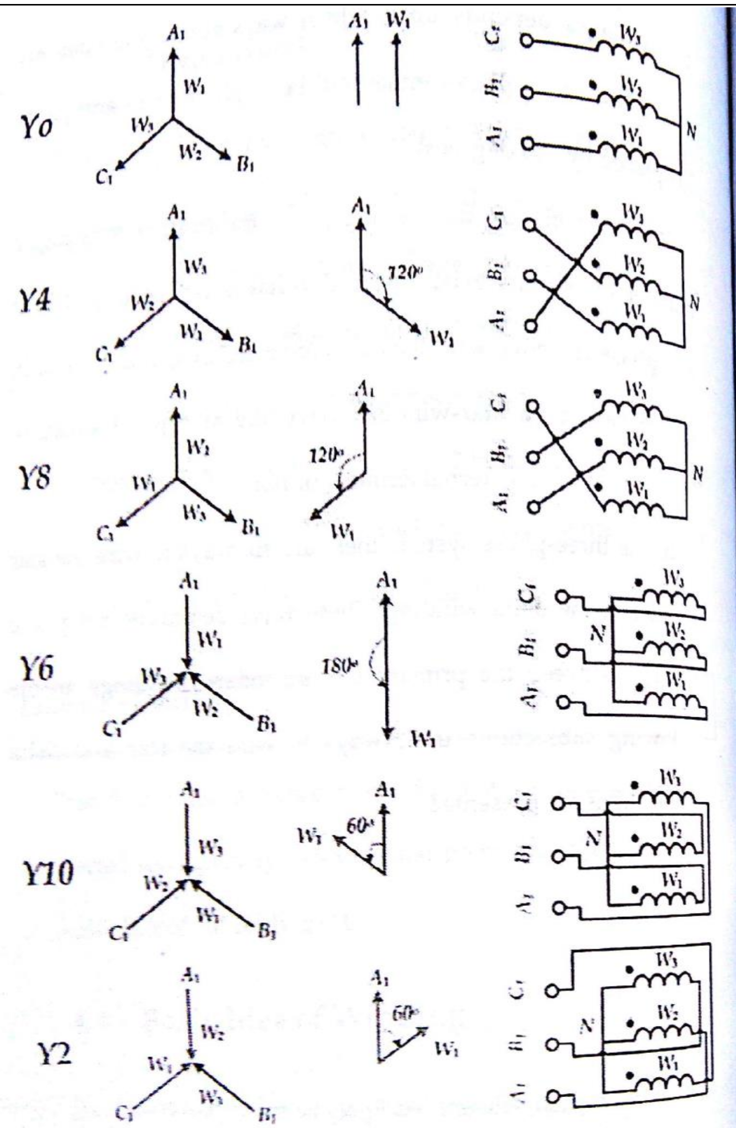


Fig. 4.3. Six Ways to wire Star Winding

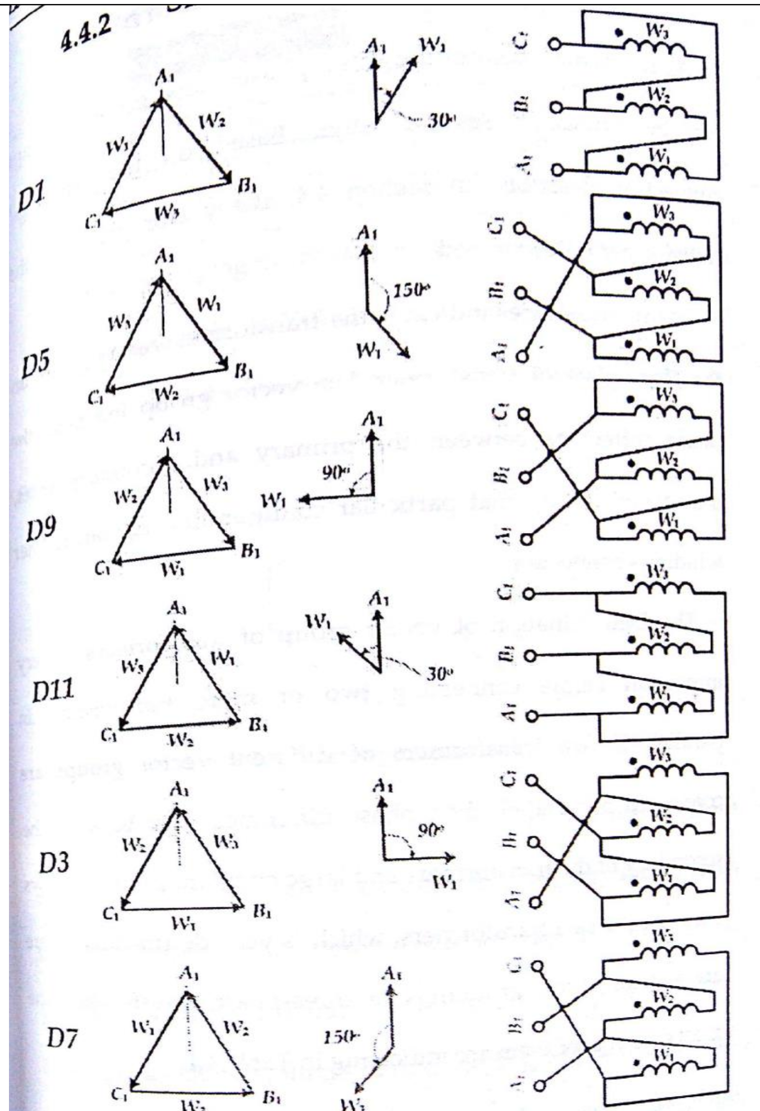


Fig. 4.4. Six Ways to wire Delta Winding

Vector Grouping of Transformer

The Vector group indicated the **phase difference** between the primary and secondary sides, introduced due to that particular configuration of transformer winding connections

- If two transformers with different vector grouping are connected in parallel then phase difference exists in the secondary of the transformers **and large circulating current flows between the two transformers, which is very detrimental.**

The are several vector grouping fir three-phase (6 for each DD,YY,DY,YD => then **36 vector groupings**

The most common of them is indicated in he table

Connection		Phase Shift
Yy0	Dd0	0
Yd1	Dy1	30 lag
Yy6	Dd6	180 lag
Yd11	Dy11	30 lead

Note : Phase voltage related to the circular rotation of clock as Yd1 : means Star HV leads Delta LV by 30 (so it's called 30 lag "output voltage **d** lags input **Y**)

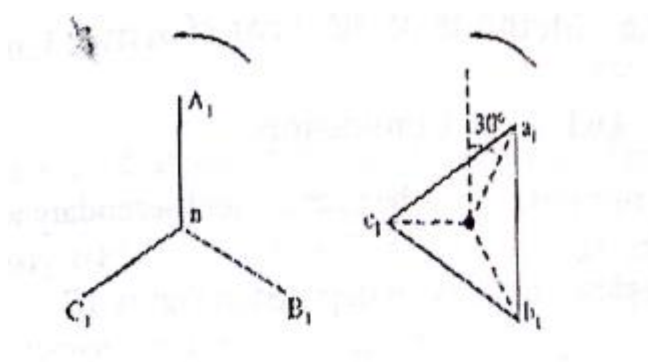


Fig. 4.5. Vector grouping of Yd1

$$cuz\ \ A_1n \parallel a_1b_1 \ \&\ B_1n \parallel b_1c_1 \ \&\ C_1n \parallel c_1a_1$$

This signifies that fluxes of one winding will be fully mututal linked with the other winding in each phase of three-phase system.

Thus, **full utilization of input flux** will be possible in this type of arrangement

That's why **Yd1** is one of important vector groupings

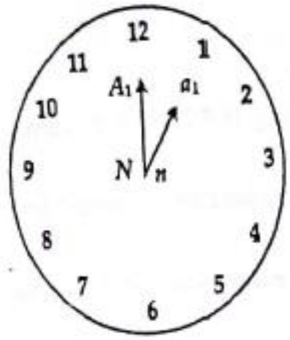


Fig. 4.6. Phase difference of vector grouping of Yd1

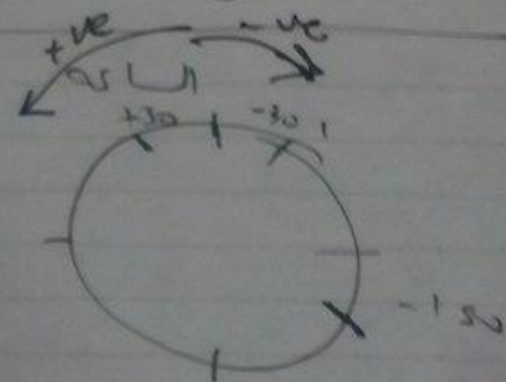
6 Y | 6 Δ

$\boxed{Y}$

V_{an}	V_{bn}	V_{cn}	+ve Seq
0	-120	120	a b c
0 12	4	8	
V_{na} 180	60 V_{nb}	-60 V_{nc}	-ve Seq
6	10	2	

$\boxed{\Delta}$

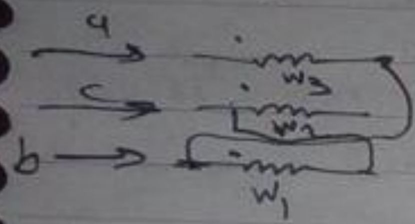
V_{ab}	V_{bc}	V_{ca}	+ve Seq
30	-90	150	
11	3	7	
-150 V_{ba}	90 V_{cb}	-30 V_{ac}	~~-ve Seq~~
5	9	1	



DATE / / SUBJECT Δ | Y | مثال

$\Delta 5$

$V_{\underline{b}a}$



$V_{\underline{b}a}$ $V_{\underline{c}b}$ $V_{\underline{a}c}$

$\boxed{\text{Vector grouping}}$

Cap H.V. small L.V. مع ملخص phase

Dy1

$\therefore \theta_{HV} - \theta_{LV} = -30$

$\therefore \theta_{HV} = \theta_{LV} - 30$

نفرض θ_{LV} بأي زاويه مناسبه

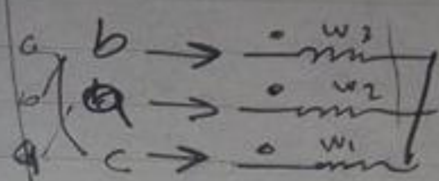
ونجيب قيمه θ_{HV} ونتأكد انها مناسبه

(يعني الزاويه اللي هتطلع

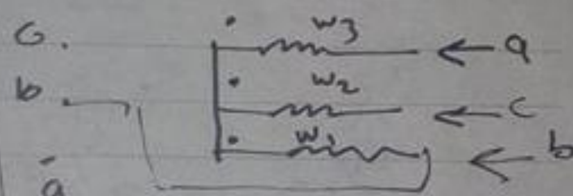
هي زاويه من زوايا الـ D)

$Y\underline{8} \rightarrow V_{cn} \rightarrow w_1$

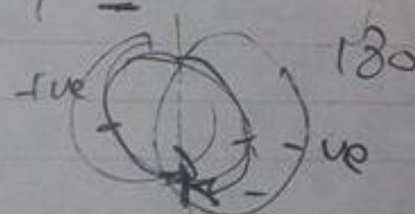
①



$Y10 \rightarrow V_{\underline{a}b}$



$Y\underline{6}$



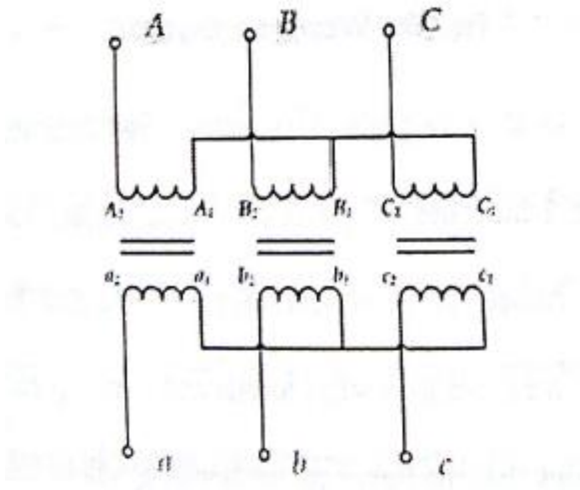
$\Delta 5$

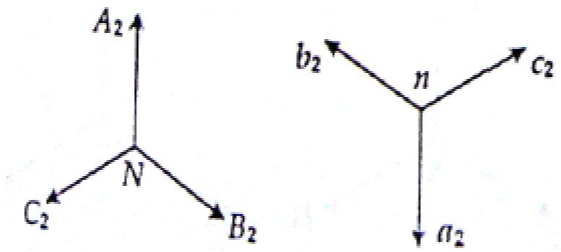
① خد الرقم × 30

② حدد الاتجاه بتاع الزاويه

Methods of 3ϕ Transformer Connections

Y-y Connection





Phase Voltage and Voltage Grouping

Analysis

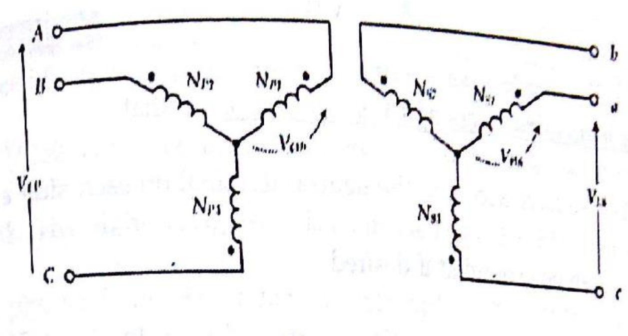
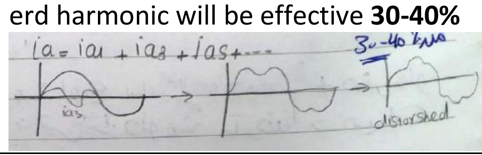


Fig. 4.11. Wiring diagram of Y-Y connected 3Ø transformer

V_{LP} $(Primary\ Line)$	$V_{LP} = \sqrt{3}\, V_{\phi P}$
V_{LS} $(\ Secondary\ Line)$	$V_{LS} = \sqrt{3}\, V_{\phi S}$
$V_{\phi P}$ to $V_{\phi S}$	$\frac{V_{\phi P}}{V_{\phi S}} = a$
$overall\ voltage\ ratio\ of\ Y - Y$	$\frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}\, V_{\phi P}}{\sqrt{3}\, V_{\phi S}} = a$
Advantages	Disadvantages
1- We have access to the neutral terminal on each side and it can be grounded if desired. 2- Can take 2 levels of voltage 3- The electrical insulation is stressed only to about **58 %** of the line voltage in a Y-connected transformer.so it's used in subtransmission 4- Rarely used	1- Without grounding the neutral terminals, the Y-y operation is satisfactory only when the three-phase load is balanced. Therefore, it is rarely used due to the **problems** with **unbalanced loads**. 2. since most of the transformers are designed to operate at or above the knee of the magnetization curve, such a design causes the induced emfs and currents to be **distorted**. The reason is as follows: Although the excitation currents are still 120° out of phase with respect to each other, their waveforms are no more sinusoidal, so these currents don't add up to zero . if neutral is not grounded, these currents are forced to add up to zero thus they affect the waveform of the induced emfs 3- if load is **150% of V_r** erd harmonic will be effective **30-40%** 

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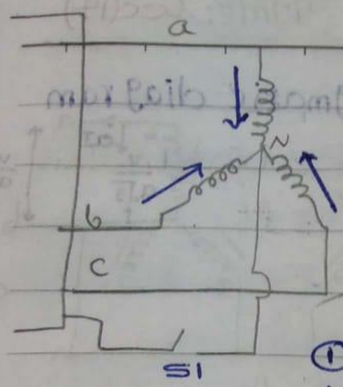


$i_A = I_{m1}\sin\omega t + I_{m3}\sin(3\omega t)$

$\cancel{i_A} = \cancel{I}_{max_3}\ \cancel{\sin}(3\omega t)$

$i_B = I_{m1}\sin(\omega t-120) + I_{m3}\sin(3\omega t-120)$

$i_C = I_{m1}\sin(\omega t+120) + I_{m3}\sin(3\omega t+120)$

• لو S1 open مفيش مسار التيارات يرجع واليه

① switch S1 open مجموعهم = صفر

$i_A + i_B + i_C = 0$

$\underbrace{I_{m}\sin\omega t + I_{m1}\sin(\omega t-120) + I_{m1}\sin(\omega t+120)}_{\text{Balanced لازم } = 0} + 3I_{m3}\sin(3\omega t)$

$\therefore 3I_{m3}\sin(3\omega t) = 0 \quad \therefore I_{m3} = 0$

• لو عندك Trans جايب منه sin = الجهد

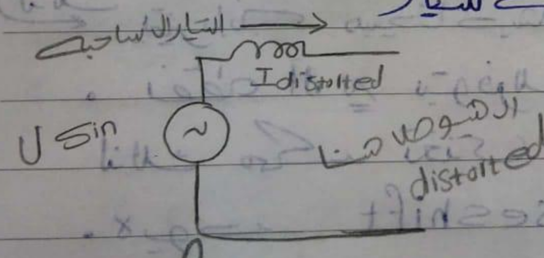
هيكون distorted

الفيز مش الـ line

• مادمنا نظر الـ Harmonics لازم نعمل تأريض

$\therefore i_A + i_C + i_B \neq 0 = I_{NN} = 3I_{m3}\sin(3\omega t)$

∴ هيظهر معايا مركبة تالتة للتيار



• لو أخدت في الاعتبار المركبة التالتة الـ losses هتزيد

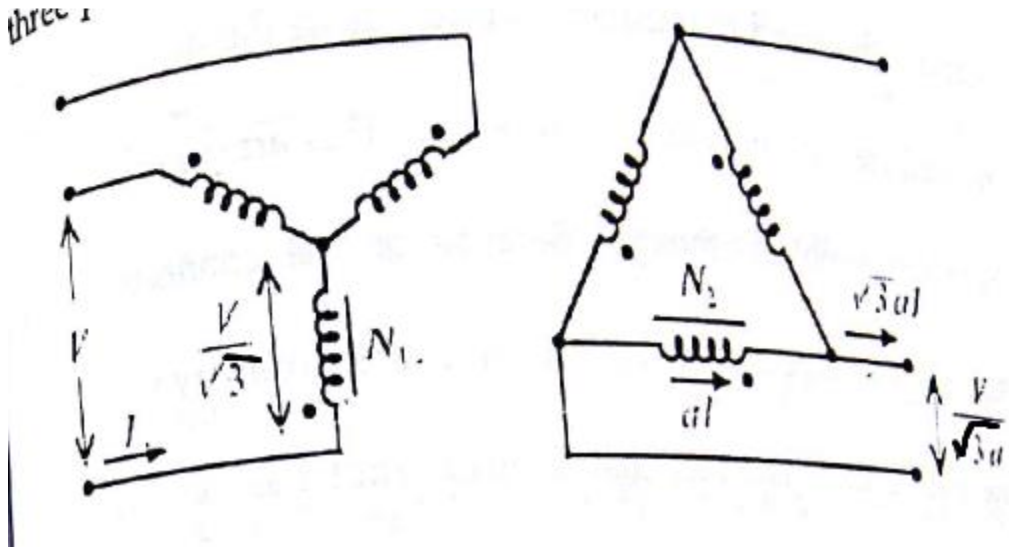
فالكفاءة هتقل

• لو التيارات مش متساوية ساعتها مجموعهم ≠ صفر ولو

انا مأرضتش التيار دا هيخرج ولو مش مأرضتش دا هيسبب

انه مدخل نقطة N تتحرك

Y-d Connection

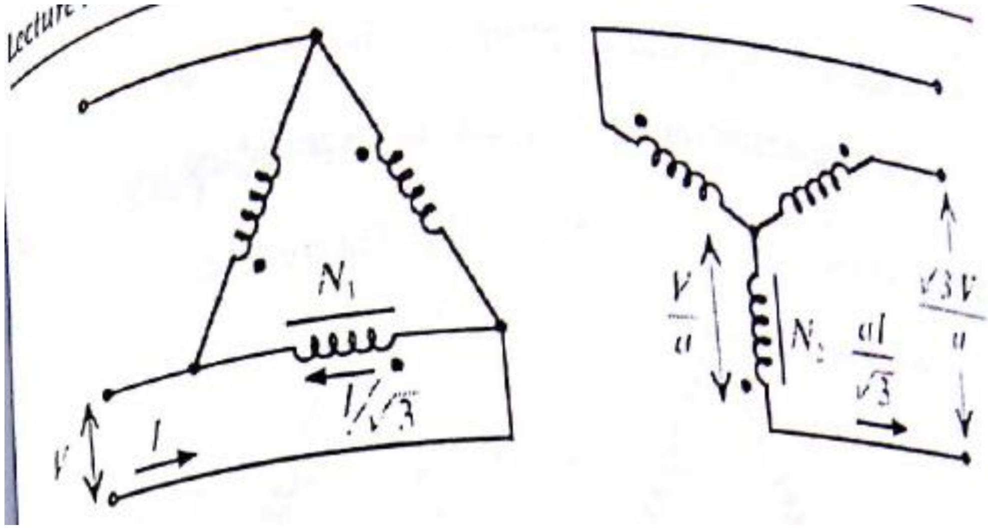


$V_{LP}\ (Primary\ Line)$	$V_{LP} = \sqrt{3}\, V_{\phi P}$
$V_{LS}\ (\ Secondary\ Line)$	$V_{LS} = V_{\phi S}$
$V_{\phi P}\ to\ V_{\phi S}$	$\frac{V_{\phi P}}{V_{\phi S}} = a$
$overall\ voltage\ ratio\ of\ Y - D$	$\frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}\, V_{\phi P}}{V_{\phi S}} = \sqrt{3}a$

Advantages	Disadvantages
1- Y-d has no problem with third harmonics as they are consumed in a circulating current on the delta side. 2- more stable with respect to unbalanced loads (as <u>delta partially redistributes any imbalance that occurs)</u>	1- Cuz of the connection, the secondary voltage is shifted 30° relative to the primary voltage of the transformer (and having a phase shift can cause **problems in paralleling** the secondaries of two transformers banks together -The phase angle of transformer secondaries must be equal if they are to be paralleld, which means that attention must be paid to the <u>direction of the 30°</u> phase shift occurring in each transformer bank to be paralled together

Paralleling : same <u>construction, phase sequence , vector grouping</u>

D-y Connection

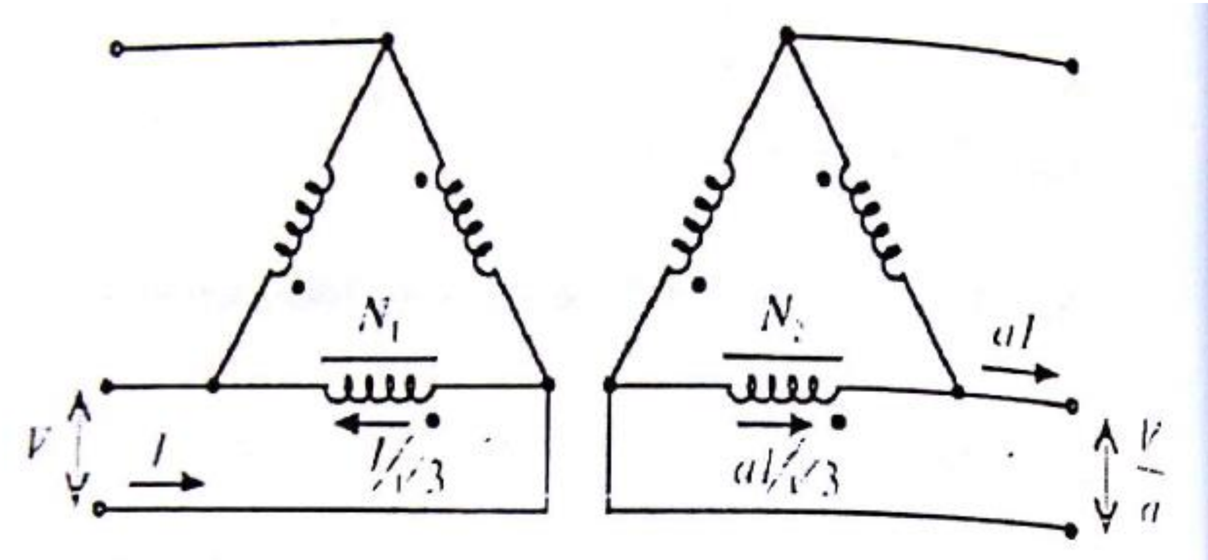


V_{LP} $(Primary\ Line)$	$V_{LP} = V_{\phi P}$
V_{LS} $(\ Secondary\ Line)$	$V_{LS} = \sqrt{3}\, V_{\phi S}$
$V_{\phi P}$ to $V_{\phi S}$	$\frac{V_{\phi P}}{\sqrt{3}\, V_{\phi S}} = a$
$overall\ voltage\ ratio\ of\ D - Y$	$\frac{V_{LP}}{V_{LS}} = \frac{V_{\phi P}}{\sqrt{3}\, V_{\phi S}} = \frac{a}{\sqrt{3}}$

Same advantages and disadvantages of Y-d

- Secondary voltage lag the primary voltage by 30°

D-d Connection



V_{LP} $(Primary\ Line)$	$V_{LP} = V_{\phi P}$
V_{LS} $(\ Secondary\ Line)$	$V_{LS} = V_{\phi S}$
$V_{\phi P}$ to $V_{\phi S}$	$\frac{V_{\phi P}}{V_{\phi S}} = a$
$overall\ voltage\ ratio\ of\ D - D$	$\frac{V_{LP}}{V_{LS}} = \frac{V_{\phi P}}{V_{\phi S}} = a$

V Connection

- Employed in emergency situation when one transformer must be removed for maintenance and continuity if service is required

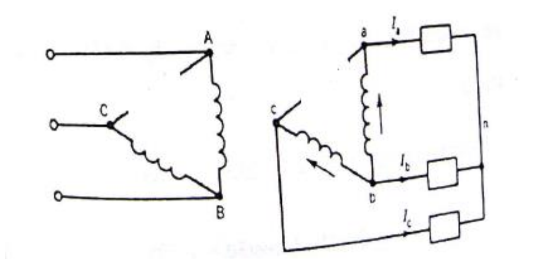
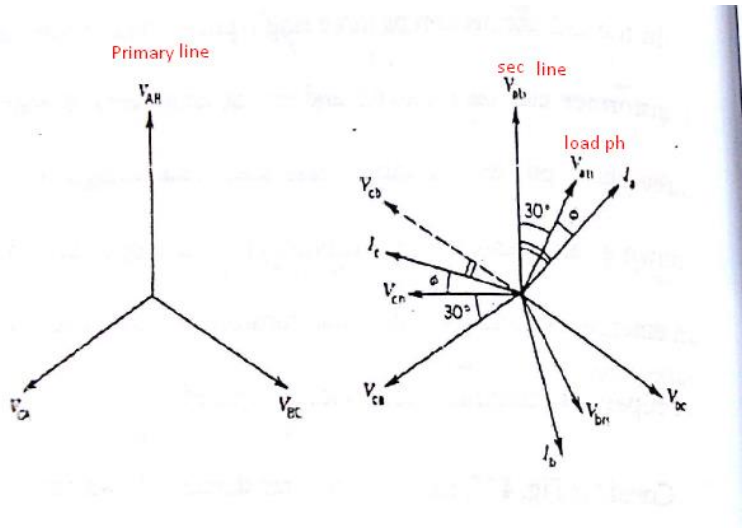


Fig. 4.15. Open-delta connection



The currents ($I_a, I_b and\ I_c\ lag\ V_{an}, V_{bn}\ and\ V_{cn}\ by\ load\ phase\ angle\ \phi$) " $for\ inductive\ load$"

$$Transformer\ windings\ ab\ and\ bc\ deliver\ power$$

$$P_{ab} = V_{ab} I_a\ \cos(30 + \phi)$$

$$P_{bc} = V_{cb} I_c \cos(30 - \phi)$$

$$|V_{ab}| = |V_{cb}| = V\ "Voltage\ rating\ of\ transormer\ secondary"$$
$$|I_a| = |I_c| = I\ \ "Current\ rating\ of\ transormer\ secondary"$$

$$\phi = 0\ for\ resistive\ load$$

$$Power\ Delievered\ by\ V$$

$$P_v = P_{ab} + P_{bc} = 2VIcos\ (30°)$$

$$Power\ of\ delta\ P_\Delta = 3VI$$

$$thus\quad \frac{P_V}{P_\Delta} = \frac{2\cos(30)}{3} = 0.58$$

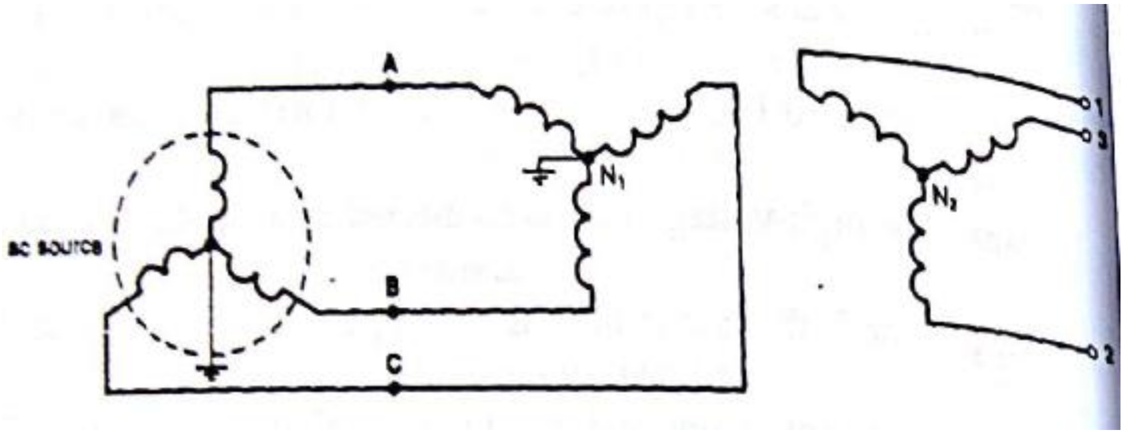
The V connection is capable of delivering 58% power without overloading the transformer

Tertiary Winding

In order to prevent the distortion in Y-y connection :

FIRST WAY:

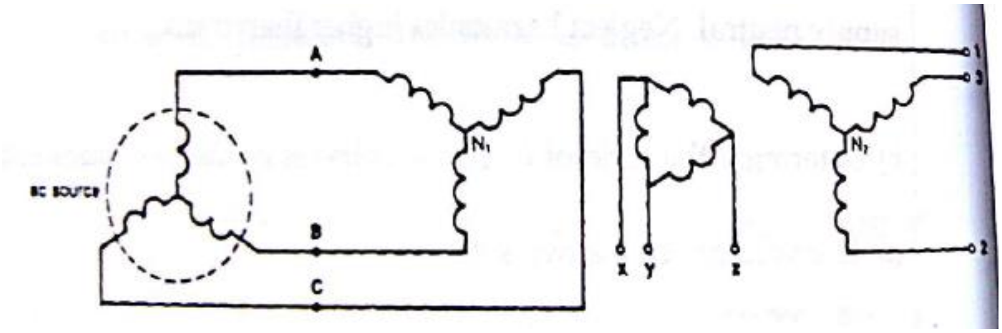
The **neutral** of primary can be connected to the neutral of the source, usually by way of **the ground** as follows;



SECOND WAY :

To provide each transformer with a third winding, called (**tertiary winding)**

Connected in delta as shown



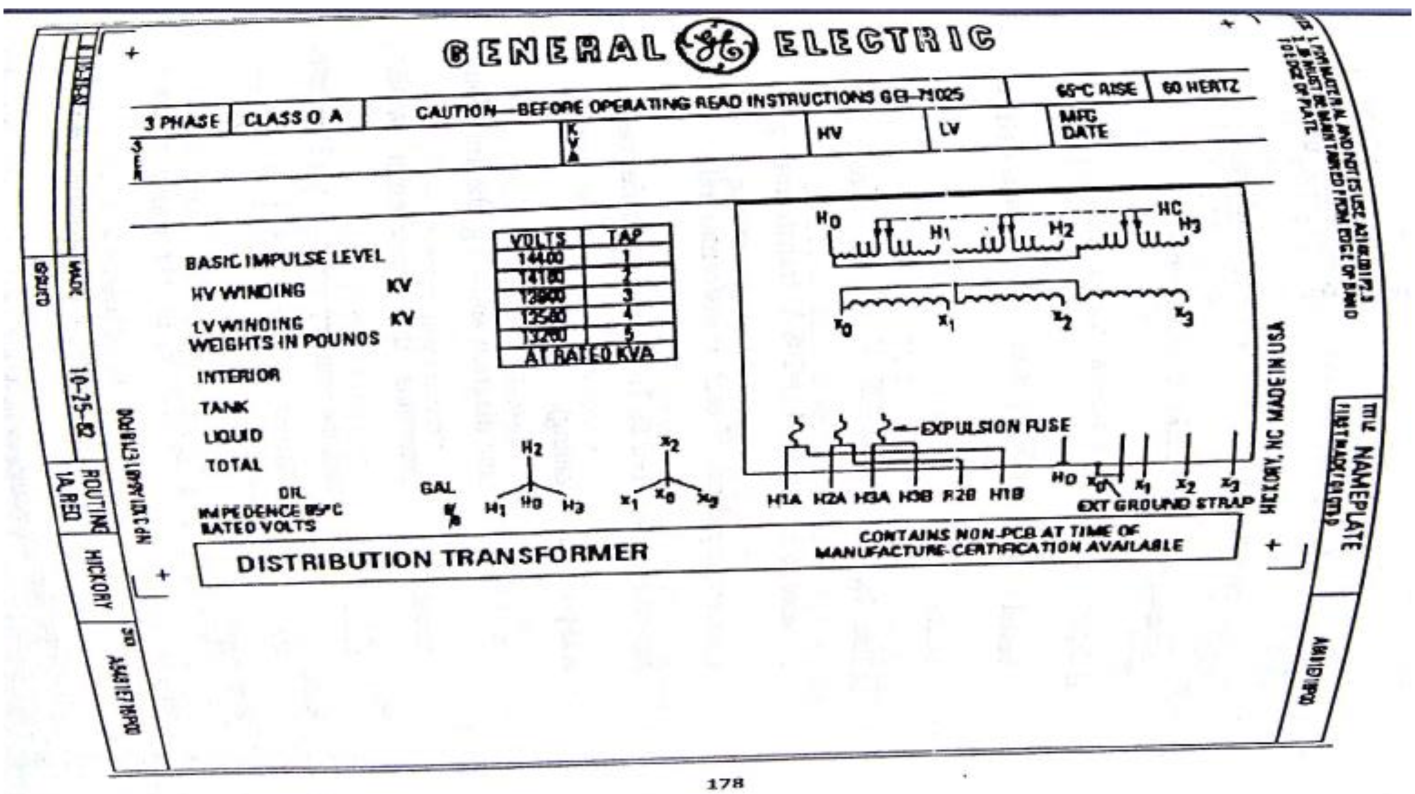
Another use of them : they provide the substation service voltage where the transformers are installed

Comparison between three-phase transformer connections

Y-Δ:	Commonly used in a **step-down** transformer, Y-connection on the HV side reduces insulation costs; the neutral point on the HV side can be grounded, stable with respect to unbalanced loads.
Δ-Y:	Commonly used in a **step-up** transformer for the same reasons as above.
Δ- Δ:	Offers the advantage that one of the transformers can be removed while the remaining two transformers can deliver three-phase power at 58% of the original bank
Y-Y:	The main advantage of a Y/Y connection is that we have access to the neutral terminal on each side and it can be grounded if desired. Without grounding the neutral terminals, the Y/Y operation is satisfactory only when the three-phase load is balanced. The electrical insulation is stressed only to about 58% of the line voltage in a Y-connected transformer. Rarely used, problems with unbalanced loads.

The Transformer Nameplate

- Rated voltage V_r
- Rated kVA S_r
- Rated frequency f_r
- Per-unit series impedance $R_{series(pu)}$
- Voltage rating for each tap $V_r\ (tap)$
- Wiring schematic $wiring\ schematic$
- transformer type designation
- References to its operating instructions



Instrument Transformer

Uses :

In AC system measures (voltage,current,power,energy,power factor,frequency)

- With protective relays for protection of power system

By :

- Step-down AC system voltage and current to measuring rating (5A, 110 V)

Advantages of Instrument Transformers

1. The **large voltage** and current of AC Power system can be measured by using small rating measuring instrument i.e. **5 A, 110 - 120 V.**

2. By using the instrument transformers, measuring instruments can be **standardized**. which results in **reduction of cost of measuring** instruments. More ever the damaged measuring instruments can be **replaced easily** with healthy standardized instruments.

3. instrument transformers provide **electrical isolation** between high voltage power circuit and measuring instruments. Which reduces the electrical insulation requirement for measuring instruments and protective circuits and assures the **safety of operators.**

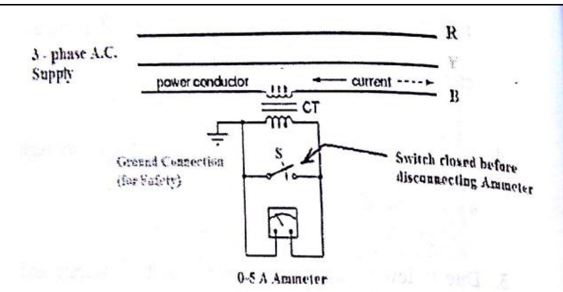
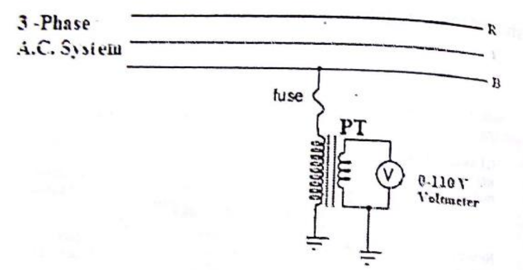
4. **Several measuring instruments** can be connected through a single transformer to power system.

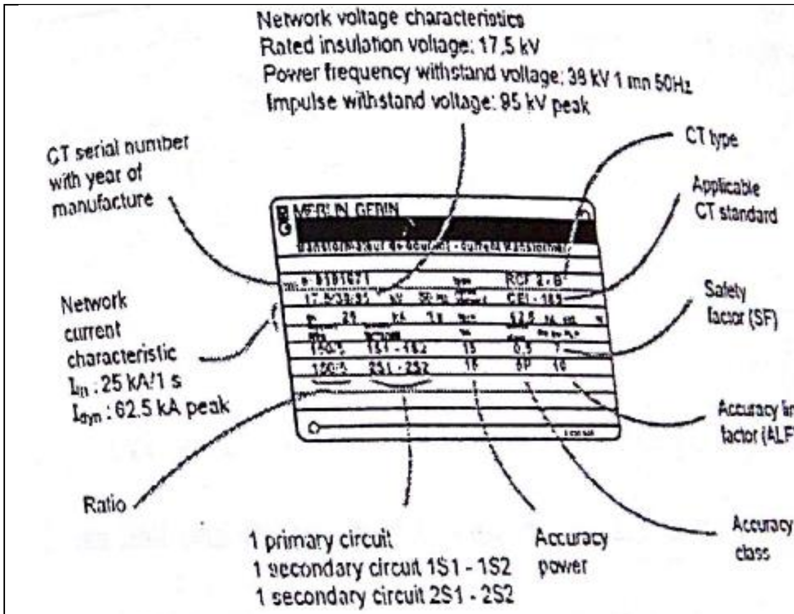
5. Due to low voltage and current level in measuring and protective circuit, there is **low power consumption** in measuring and protective circuits.

Types of instrument Transformers

1- Current Transformer (C.T)
2- Potential Transformer (P.T)

Current Transformer Vs Potential Transformer

Current Transformer (C.T.)	Potential Transformer (P.T.)
	
Connected in series with power circuit “Series Transformer”	Connected in parallel with power circuit Steps down voltage to make it feasible to be measure at rating **(110: 120 V)** - Primary is connected across the line (generally between on line and earth). “parallel transformer”
Primary of C.T. is having very few turns. Sometimes bar primary is also used.	Primary is having large number of turns -
The secondary is having large no. of turns.	Secondary having few turns
Secondary is connected to Ammeter	Secondary is connected to Voltmeter
Secondary works almost in short circuited condition	Secondary works almost in open circuited condition
Primary current depends on power circuit current	Primary current depends on secondary burden
Primary current and excitation vary over wide range with change of power circuit current	Primary current and excitation variation are restricted to a small range
One terminal of secondary is earthed to avoid large voltage on secondary with respect to earth. Which in turns reduces the chances **of <u>insulation breakdown</u>** and **<u>protect the operator</u>** against high voltage.	On terminal of secondary can be earthed **<u>for safety</u>**
More over before disconnecting the ammeter secondary is short-circuited through a switch “S” as shown in fig, <u>to avoid the high voltage build up across the secondary</u>	Secondary can be used in open circuit condition



Name plate contains

1- CT serial number with year manufacture
2- Network current ch/c $I_m = 25\frac{kA}{1s}$

$$I_{ayn} = 62.5\ kA\ peak$$

3- Ratio
4- CT type
5- Applicable CT standard
6- Safety factor (SF)
7- Accuracy Limit factor (ALF)
8- Accuracy class
9- Accuracy power
10- (1 primary circuit,1secondary circuit 1S1-1S2, 1 secondary circuit 2S1-2S2)

Inrush Current

$$at\ Steady\ State\ \ I_{\phi}(magn.current\ ) < 5\%\ of\ I_{rated}$$

But when it's first connected, large inrush current will flow during transient period

$$I_{inrush}\ can\ be\ \ \mathbf{10\ to\ 20}\ times\ the\ rated\ current$$

- It's important in determining the mechanical stresses that could occur in transformer winding
- In designing the protective system for the transformer

- It's magnitude depends on <u>instant of voltage wave at which the transformer is connected</u>

Analysis

Consider a transformer whose core is initially unmagnetized The transformer primary winding is now connected to a supply voltage

$$v = \sqrt{2}V\ \sin(\omega t)$$

Neglecting core losses and primary winding resistance

$$v = N\frac{d\phi}{dt}$$

$$\phi = \frac{1}{N}\int v\ dt$$

Consider two cases as follows

Case 1	Case 2
- Transformer is connected when voltage was **Maximum** - Variation of flux - $\phi = \phi_{Max}\sin(\omega t - 90°)\ for\ \omega t > 90°$	Transformer connected when phase was zero كمل ع معادلات فوق $\phi = \frac{\sqrt{2}V}{N}\int_0^t \sin\omega t\ \ dt$ $= \frac{\sqrt{2}V}{\omega N}\ (\ 1 - \cos\omega t)$

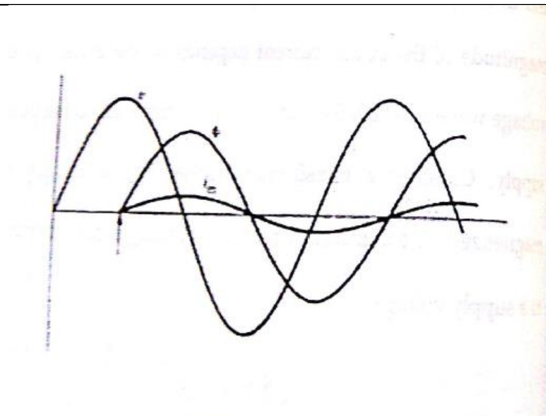


Fig. 2.36. Transformer Inrush Current (case-1)

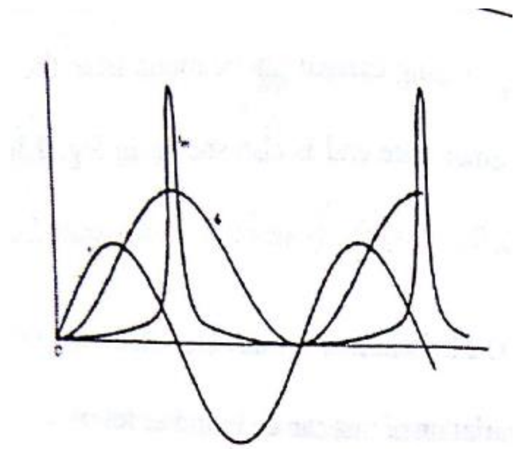
Inrush current can be deduced from the B-H curve of transformer core

As in fig

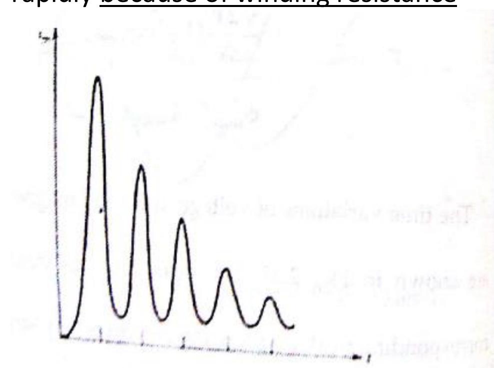
No inrush current will flow and transformer is in steady state since start

$$= \phi_{Max} - \phi_{Max}\cos(\omega t)$$

The time variations of voltage, flux, and magnetizing current are shown in Fig. 2.37. The peak **flux has doubled** and the corresponding peak **magnetizing current is very large** <u>**because of core saturation.**</u>



In practice, the large inrush current will decay rapidly <u>because of winding resistance</u>



<u>NOTE :</u>

In three-phase transformers there is always inrush current because for one phase if it's maximum it's not maximum for another

Extra Important Tables

	I_L	I_ϕ	V_L	V_ϕ
Yy	S	S	S	D
Yd	S	D	S	S
Dy	S	D	S	S
Yyn	D	D	S	S
DD	S	S	S	S

$3-\phi\ \ bank\ S_{3\phi} = 500\ kVA\ \ \ 34.5:\ 11\ kV$
$the\ rating\ of\ 1-\phi\ if$

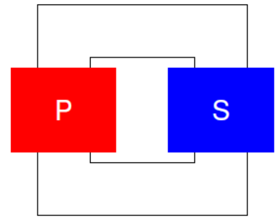
	$V_{P\phi}$	$V_{S\phi}$	$a=\frac{V_{p\phi}}{V_{s\phi}}$	S_ϕ
$Y-Y$	$\frac{34.5}{\sqrt{3}}$	$\frac{11}{\sqrt{3}}$	$\frac{34.5}{11}$	$\frac{500}{3}$
$\Delta-\Delta$	34.5	11	$\frac{34.5}{11}$	$\frac{500}{3}$
V	34.5	11	$\frac{34.5}{11}$	$\frac{500}{\sqrt{3}}$

Basics of Transformer Design (Equations)

Symbols

$\boldsymbol{\phi_m}$	Main flux, Wb
$\boldsymbol{B_m}$	Maximum flux density , Wb/m^2
$\boldsymbol{\delta}$	Current density A/m^2
$\boldsymbol{A_{gi}}$	Gross Net core area, m^2
$\boldsymbol{A_i}$	Net core area, m^2 $= \text{stacking factor} \times \text{gross core area}$
$\boldsymbol{A_c}$	Area of copper in window ,m^2
$\boldsymbol{A_w}$	Window area , m^2
$\boldsymbol{D}$	Distance between core centres ,m
d	Diameter of circumscribing circle , m
$\boldsymbol{k_w}$	Window space factor
$\boldsymbol{f}$	frequency
$\boldsymbol{E_t}$	Emf per turn
$\boldsymbol{T_p, T_s}$	Number of turns in primary or secondary
$\boldsymbol{I_p, I_s}$	Current in primary and secondary
$\boldsymbol{V_p, V_s}$	Terminal voltage of primary and secondary
$\boldsymbol{a_p, a_s}$	Conductor area of primary and secondary ,m^2
$\boldsymbol{l_i}$	Mean length of flux path in iron, m
$\boldsymbol{L_{mt}}$	Length of mean turn of transformer windings
$\boldsymbol{G_i}$	Weight of active iron, kg
$\boldsymbol{G_c}$	Weight of copper , kg
$\boldsymbol{g_i}$	Weight iron per m^3 , kg
$\boldsymbol{g_c}$	Weight copper per m^3,kg
$\boldsymbol{p_i}$	Loss in iron per kg, W
$\boldsymbol{p_c}$	Loss in copper per Kg , W

Single-Phase Transformer

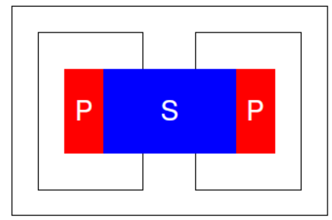


$$Voltage\ per\ turn = E_t = \frac{E}{T} = 4.44\, f\phi_m$$

Window cantains one primary and one secondary so

$$A_c = T_p a_p + T_s a_s$$

The current density the same $a_p = \frac{I_p}{\delta}$, $a_s = \frac{I_s}{\delta}$



$$total\ conductor\ area\ A_c = T_p \frac{I_p}{\delta} + T_s \frac{I_s}{\delta} = \frac{T_p I_p + T_s I_s}{delta}$$

$$\boldsymbol{A_c = \frac{2AT}{\delta}}$$

Window space factor

$$K_w = \frac{A_c}{A_w} \rightarrow \ A_c = K_w A_w$$

$$\frac{2AT}{\delta} = K_w A_w$$

$$\therefore AT = \frac{K_w A_w \delta}{2}$$

Rating of single phase transformer in kVA

$$Q = V_p I_p \times 10^{-3} = E_p I_p \times 10^{-3}$$

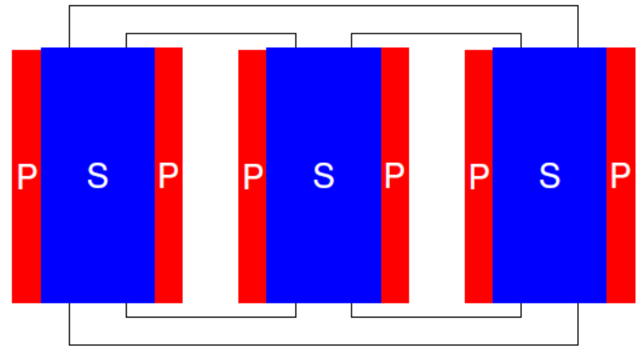
$$Q = E_t\, T_p\, I_p \times 10^{-3} = E_t * AT \ \times 10^{-3}$$

$$Q = 4.44\, f\phi_m * \frac{A_w K_w \delta}{2} \times 10^{-3}$$

$$\therefore \ Q = 2.22\, f\, B_m\ A_i\, A_w\, K_w\, \delta\ \times 10^{-3}\ kVA$$

Three Phase Transformer

The window contain <u>two</u> primary and <u>two</u> secondary



$$A_c = 2(T_p a_p + T_s a_s)$$

$$A_c = 2T_p \frac{I_p}{\delta} + 2T_s \frac{I_s}{\delta}$$

$$A_c = \frac{4AT}{\delta}$$

$$A_c = \frac{4AT}{\delta} = K_w A_w$$

$$AT = \frac{K_w A_w \delta}{4}$$

Rating of three phase transformer in kVA

$$Q = 3V_p I_p \times 10^{-3} = 3\, E_{pI_p} \times 10^{-3}$$

$$Q = 3 * E_t\, T_p I_p \times 10^{-3} = 3 * E_t * AT \times 10^{-3}$$

$$Q = 3 * 4.44 f\phi * \frac{K_w A_w \delta}{4} \times 10^{-3}$$

$$Q = 3.33\ f\, B_m A_i A_w\, K_w\, \delta \ \times 10^{-3}$$

Output Equation in Volt per turn (for 1-ϕ)

$$Q = 4.44\ f\ \phi_m * AT \times 10^{-3}$$

$$r = \frac{\phi_m}{AT} \rightarrow \quad AT = \frac{\phi_m}{r}$$

$$Q = 4.44\ f\phi_m\ \frac{\phi_m}{r} \times 10^{-3}$$

$$Q = 4.44 \frac{f}{r} \times 10^{-3}\ \phi_m^2$$

$$\phi_m = \sqrt{\frac{r * 10^3}{4.44\ f}}\ \sqrt{Q}$$

$$E_t = 4.44\ f\ \phi_m = 4.44\ f * \sqrt{\frac{r \ \times 10^3}{4.44\ f}}\ \sqrt{Q} = \sqrt{4.44 f * r * \ 10^3}\ \sqrt{Q}$$

$$E_t = \sqrt{4.44 f * r * \ 10^3}\ \sqrt{Q}$$

$$E_t = K\sqrt{Q}$$

K is constant for a transformer of a given type, service and method of construction.

		K
Single phase	Shell type	1: 1.2
	Core type	0.75: 0.85
Three phases	Shell Type	1.3
	Core type (distribution)	0.45
	Core type (Power)	0.6: 0.7

Ratio of Copper Loss to Iron Loss

$$copper\ loss\ per\ m^3 :$$

$$p_c = \frac{RI^2}{V} = \rho\frac{l}{A} * (A\delta)^2 * \frac{1}{Al}$$

$$p_c = \rho\delta^2$$

$$\frac{P_i}{P_c} = \frac{p_i G_i}{p_c G_c}$$

When the densities of the iron and copper are determined, the loss per kg for iron and copper are determined. THEN The ratio of **weight of iron to weight of copper** can be easily found.

Core Design

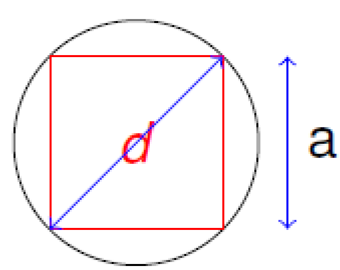
Rectangular Core

For core type **distribution** transformers and **small power** transformers for **moderate and low voltage**. The ratio of width to depth varies between **1.4 to 2**. Rectangular **shaped coils** are used for rectangular core.

Square Core

- When circular coils are required.

$$A_{gi} = a^2 = \left(\frac{d}{\sqrt{2}}\right)^2 = 0.5\,d^2$$



Without stacking factor

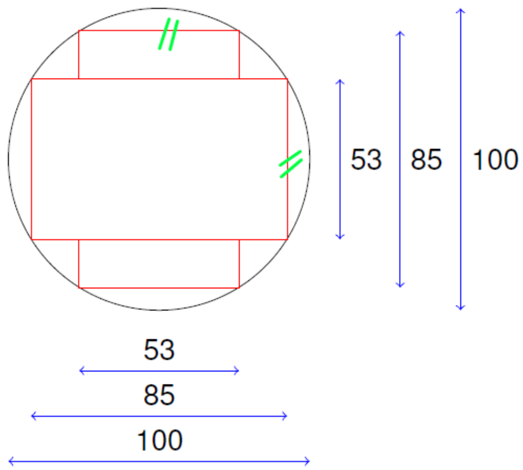
$$\frac{Gross\ core\ area}{area\ of\ circle} = \frac{0.5d^2}{\pi\frac{d^2}{4}} = 0.64$$

with stacking factor = 0.9

$$\frac{Net\ core\ area}{Area\ of\ circle} = \frac{0.9 * 0.5d^2}{\pi \frac{d^2}{4}} = 0.58$$

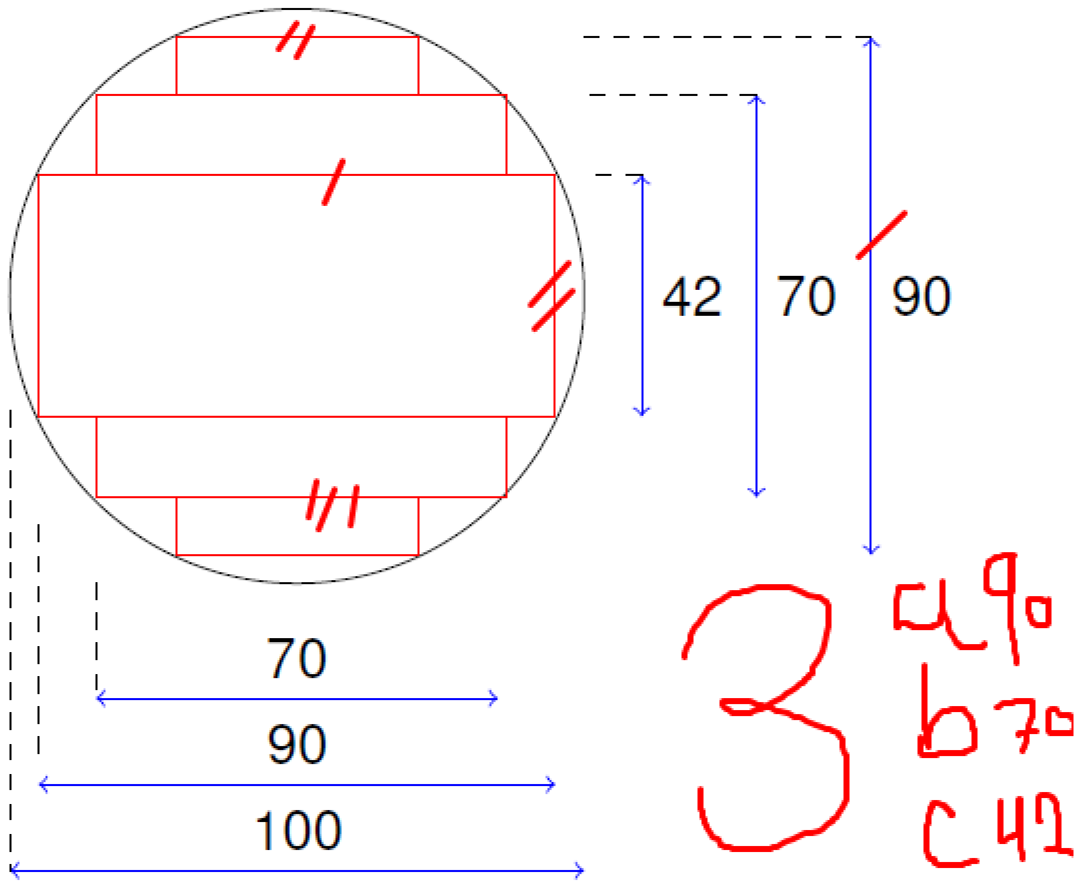
---

2 stepped core



2 different dimensions **(a : 85 , b : 53)**

3 stepped core



3 different dimensions **(a : 90 , b :70 , c : 42)**

% of circumscribing	Square	2 Step	3 step	4 step
Gross core area A_{gi}	64	79	84	87
Net core area A_i	58	71	75	78
Net core area kd^2	0.45	0.56	0.6	0.62

نلاحظ الزياده في النسبه كل ما نزود عدد ال steps

EXAMPLES

The ratio of flux to full load mmf in a 400kVA, 50Hz, single phase core type power transformer is 2.4×10^{-6}. Calculate the net iron area and the window area of the transformer. Maximum flux density in the core is $1.3\mathrm{Wb/m^2}$, current density is $2.7\ \mathrm{A/mm^2}$ and window space factor is 0.26. Also, calculate the full load mmf.

Answer

$$
\begin{aligned}
Q &= 400\ \mathrm{kVA}\\
f &= 50\ \mathrm{Hz}\\
\Phi_m/AT &= 2.4 \times 10^{-6}\\
B_m &= 1.3\ \mathrm{Wb/m^2}\\
\delta &= 2.7\ /\mathrm{m^2}\\
K_w &= 0.26\ \mathrm{m^2}
\end{aligned}
$$

اجيب ال E_t عشان منها اجيب ال $\phi = \frac{E_t}{4.44f}$ ومنها اجيب $A_i = \frac{\phi_m}{B_m}$

من قانون ال Q اخد ال A_w في طرف واجيبها

ال AT full load ممكن من بعدا ما جبت ال $\frac{\phi}{AT} = 2.4 * 10^{-6}$ اخدها ف طرف لوحدها

$$E_t = K\sqrt{Q}$$

$$E_t = \sqrt{4.44fr.10^{-3}}\sqrt{Q}$$

$$E_t = \sqrt{4.44f\frac{\Phi_m}{AT}.10^{-3}}\sqrt{Q}$$

$$E_t = \sqrt{4.44 \times 50 \times 2.4 \times 10^{-6} \times 10^3}\sqrt{400}$$

$$E_t = 0.73 * 20 = 14.64\mathrm{V}$$

$$\Phi_m = \frac{E_t}{4.44f} = \frac{14.64}{4.44 \times 50} = 0.066\mathrm{Wb}$$

$$A_i = \frac{\Phi_m}{B_m} = \frac{0.066}{1.3} = 0.0507\mathrm{m^2}$$

$$\boxed{A_i = 0.0507\mathrm{m^2}}$$

Note:

if the area is square the side length is $22.5\mathrm{cm}$

$$A_w = \frac{Q}{2.22fB_mK_w\delta A_i \times 10^{-3}}$$

$$A_w = \frac{400}{2.22 \times 50 \times 1.3 \times 0.26 \times 2.7 \times 10^6 \times 0.0507 \times 10^{-3}}$$

$$\boxed{A_w = 0.088\mathrm{m^2}}$$

Design a 25kV A, 1100/433V, 3 phase, delta/star, core type, oil immersed natural cooled distribution transformer. The transformer is provided with tapings $\pm 2\frac{1}{2}$, 5% on the h.v. winding. Maximum temperature rise not to exceed 45°C with mean temperature rise of oil is 35°C.

Core design :

$$get\ E_t \rightarrow \phi_m \rightarrow \ put\ B = 1 \rightarrow \ get\ A_i \rightarrow assume\ 2\ stepped \rightarrow A_i = 0.56d^2\ get\ d$$
$$get\ a\ , b$$

Window design:

$$put\ K_w = 0.18\ (MAX\ 0.3`)\ for\ a\ small\ transformer\ , put \delta = 2.3$$

$$from\ Q\ \ equation\ get\ A_w$$
$$assume\ ratio\ of\ hight\ to\ width = 2.5\ get\ H_W\ and\ W_W$$

$$Distance\ between\ adjacent\ core\ centres(D) = W_w + d$$

Yoke design :

$$assume\ area\ of\ yoke\ 1.2\ times\ of\ the\ limb$$

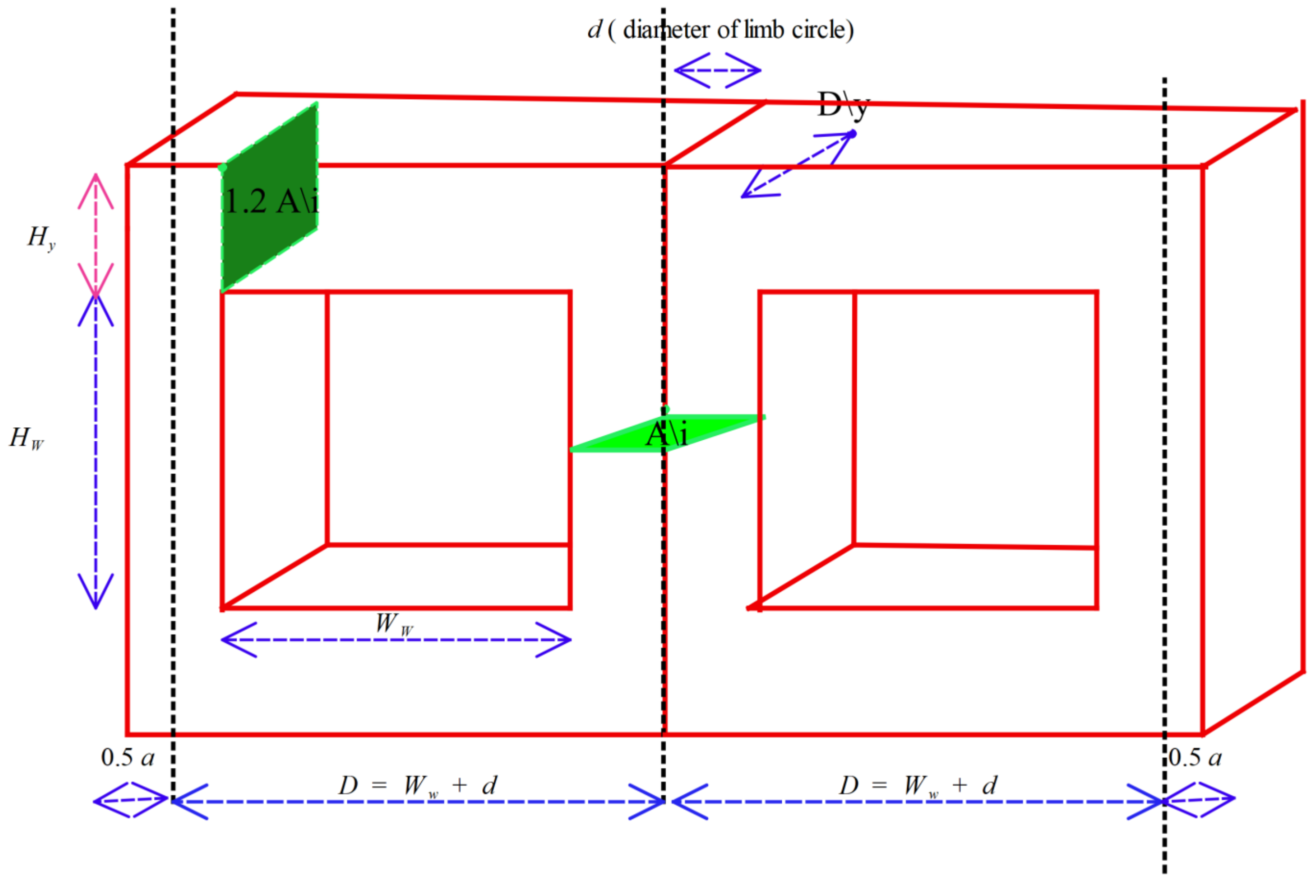
$$B_{yoke} = \frac{B_m}{1.2}$$

$$net\ area\ of\ yoke = 1.2 * A_i * 10^3$$
$$gross\ area = \frac{(net\ area)}{k_s(0.9)}$$

$$assume\ rectangular\ yoke\ assume\ D_y = 114\ mm\ then\ Hy = \frac{gros}{114}$$

$$Height\ of\ frame = H = H_w + 2H_y$$
$$width\ of\ fram = 2D + a$$

$$depth\ of\ frame = D_y$$



افترض الرجل وال yoke هم stepped بابعاد d a b

Answer - Core Design

The value of K from the table for a distribution transformer, core type.

$$K = 0.45$$

Volt per turn

$$E_t = K\sqrt{Q} = 0.45\sqrt{25} = 2.25\mathrm{V}$$

Core flux

$$\Phi_m = \frac{E_t}{4.44f} = \frac{2.25}{4.44 \times 50} = 0.010135\mathrm{Wb}$$

Assume $B_m = 1\mathrm{T}$:

$$A_i = \Phi_m / B_m = 0.010135\mathrm{m}^2$$

using 2 stepped core

$$A_i = 0.56d^2$$

$$d = 0.1345\mathrm{m} = 134.5\mathrm{mm}$$

$$d = 134.5\mathrm{mm}$$

$$a = 0.85 * 134.5 = 114\mathrm{mm}$$

$$b = 0.53 * 134.5 = 73\mathrm{mm}$$

Window Dimensions

- The window space factor can be found for small transformer assume $K_w = 0.18$
- assume current density $\delta = 2.3\ \mathrm{A/m^2}$

$$Q = 3.33 f B_m K_w \delta A_w A_i \times 10^{-3}$$
$$25 = 3.33 \times 50 \times 1.0 \times 0.18 \times (2.3 \times 10^6) \times A_w \times 0.010135 \times 10^{-3}$$
$$A_w = 0.0358\mathrm{m}^2 = 35.8 \times 10^3\mathrm{mm}^2$$

- Taking the ratio of height to width as 2.5

$$H_w \times W_w = 35.8 \times 10^3$$
$$2.5 W_w = 35.8 \times 10^3$$

Width of window:

$$W_w = 120\mathrm{mm}^2$$

Height of window:

$$H_w = 300\mathrm{mm}^2$$

Note:

Area of window provided $A_w = 300 \times 120 = 36 \times 10^3\ \mathrm{mm}^2$

Distance between adjacent core centers:

$$D = W_w + d = 120 + 135 = 225\mathrm{mm}$$

Yoke Design

The area of yoke is taken as 1.2 times that of the limb.
Flux density in yoke $= 1/1.2 = 0.833\ \mathrm{Wb/m^2}$
Net area of yoke $= 1.2 \times 10.135 \times 10^3 = 12.16 \times 10^3\ \mathrm{mm}^2$
Gross area of yoke = $12.16 \times 10^3/0.9 = 13.5 \times 10^3\ \mathrm{mm}^2$
Taking the section of the yoke as rectangular:

$$\texttt{Depth of yoke} D_y = a = 114\mathrm{mm}$$

$$\texttt{Height of yoke} H_y = a = 13.5/114\mathrm{mm}$$

Overall Dimensions of Frame

Height of frame:

$$H = H_w + 2H_y = 300 + 2 \times 114 = 528\mathrm{mm}$$

Width of frame:

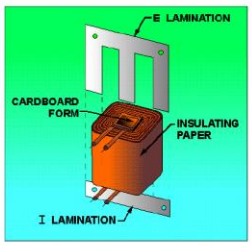
$$W = 2D + a = 2 * 255 + 114 = 624\mathrm{mm}$$

Depth of frame:

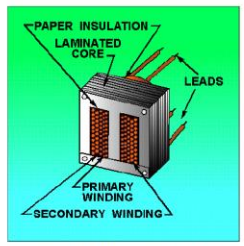
$$D_y = 114\mathrm{mm}$$

Transformer DESIGN (NAZARY)

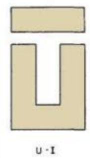
Core and Shell Types Transformers



Exploded view of shell-type transformer construction.



Cutaway view of shell-type core with windings.



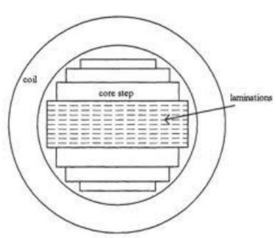
Typical Data Sheet/SMU/4000 Family

Dimensions and drillings

Reference Number	Rated Thermal Output (VA)	Admissible Instant. Output (VA)	Dimensions			Drillings			Dissipated Power (W)	Efficiency (%)	Weight (Kg)
			L	P	H	A	B	G			
SMU/4002	30	63	75	75	78	55	45	4,5	7,2	80,1	1,1

Stepped Lamination Core

Typical Core



METHODS OF COOLING

The kinds of cooling medium and their symbols adopted by I.S. 2026 (Part 11)-1977 are:

O(a) Mineral oil or equivalent flammable insulating liquid

L (b) Non-flammable synthetic insulating liquid

G (c) Gas

W(d) Water

A (e) Air

The kinds of circulation for the cooling medium and their symbols are:

N(a) Natural

F(b) Forced (Oil not directed)

D(c) Forced (Oil directed)

Cooling Method Labels

Each cooling method of Transformer is identified by four symbols.

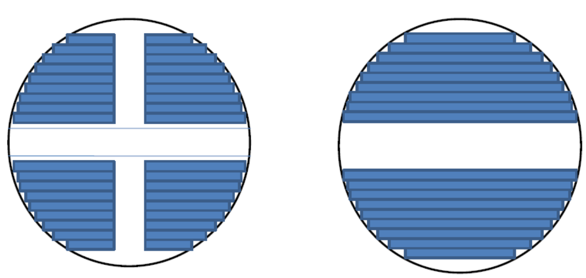
1	2	3	4
The kind of cooling medium in contact with winding	The kind of circulation for the cooling medium	The cooling medium that is in contact with the external cooling system	The kind of circulation for the external medium.

EX : OilimmersedTransformerwithnaturaloilcirculationandforcedairexternalcoolingisdesignated.

ONAF

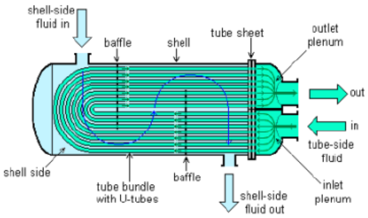
Cooling

Ventilation Ducts

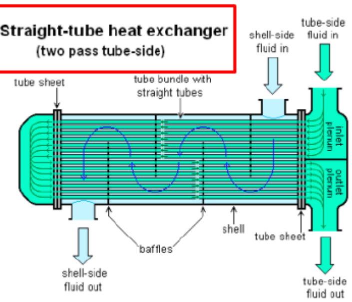


Heat Exchange Design

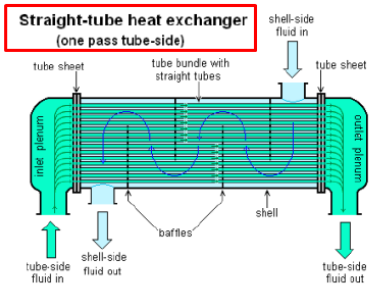
U-tube heat exchanger



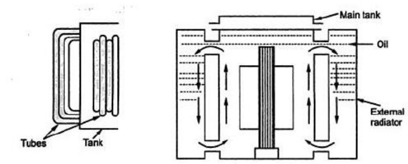
Straight-tube heat exchanger (two pass tube-side)



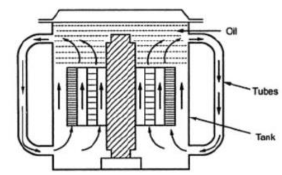
Straight-tube heat exchanger (one pass tube-side)



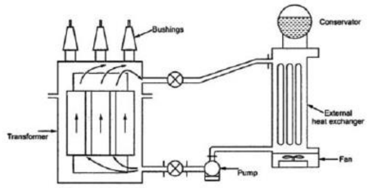
Cooling of transformers



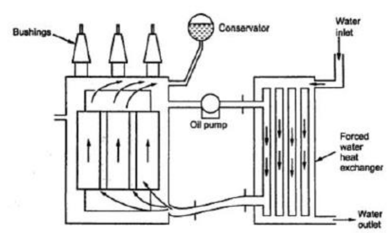
Tanks with tubes and radiator



Oil immersed transformer



Oil forced air forced cooling method

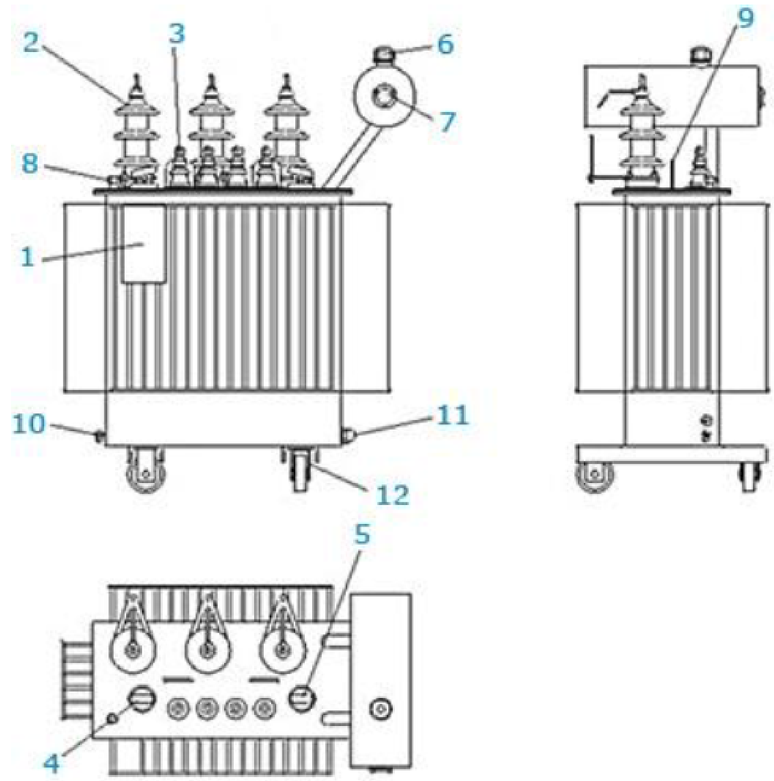


Oil forced water forced cooling method

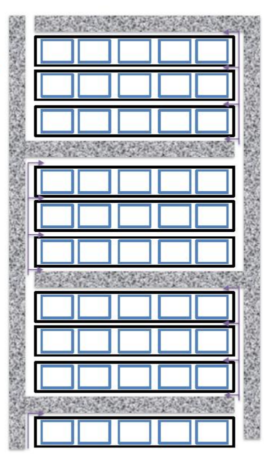
Earthling of Transformer

Standard Fittings

1- Rating plate
2- H.V. bushings
3- L.V. bushings
4- H.V. tapping switch
5- H.V. double primary voltage switch
6- Oil filling and plug
7- Conservator with oil level indicator
8- Thermometer pocket
9- Lifting lugs
10- Earthing terminal
11- Oil drain valve
12- Rollers or skids

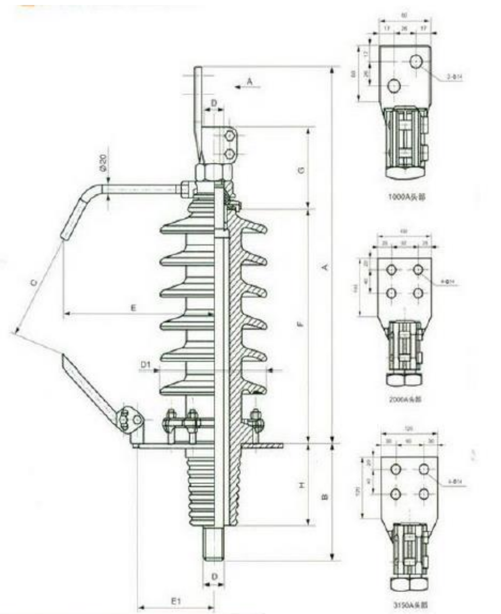


Directed Flow of
oil in transformers



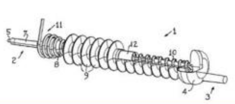
ريشة

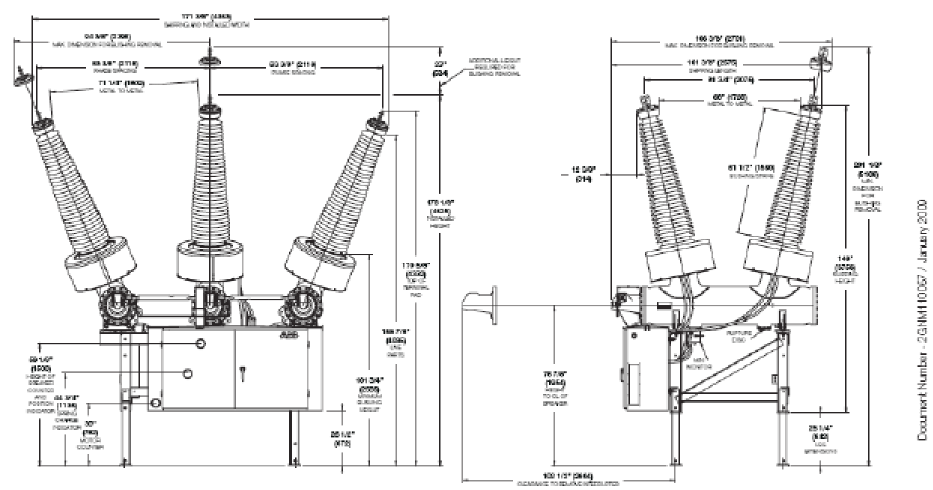
High Voltage Bushings



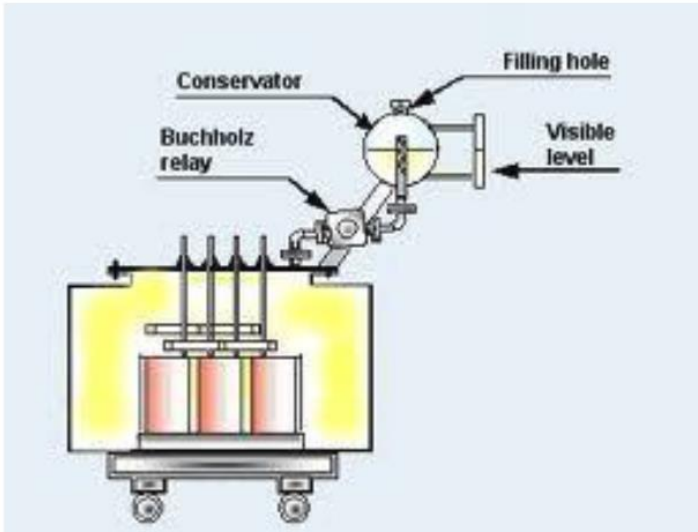
代　号 (Code)	型号 (Type)	A	B	C	D	D1	E	E1	F	G	H	Tank Hole	重量 (Weight)
XR.286.2534.1	52kv/1000 A	730	253	305	M30X2	Φ250	350	175	509	148	176	Φ135	35.2kg
XR.286.2534.4	52kv/2000 A	807	253	305	M42X3	Φ250	350	175	509	178	176	Φ135	44.9kg
XR.286.2534.5	52kv/3150 A	836	253	305	M48X3	Φ250	355	180	509	183	176	Φ135	49.2kg

High Voltage Bushings





Buchholz Relay



Buchholz Relay

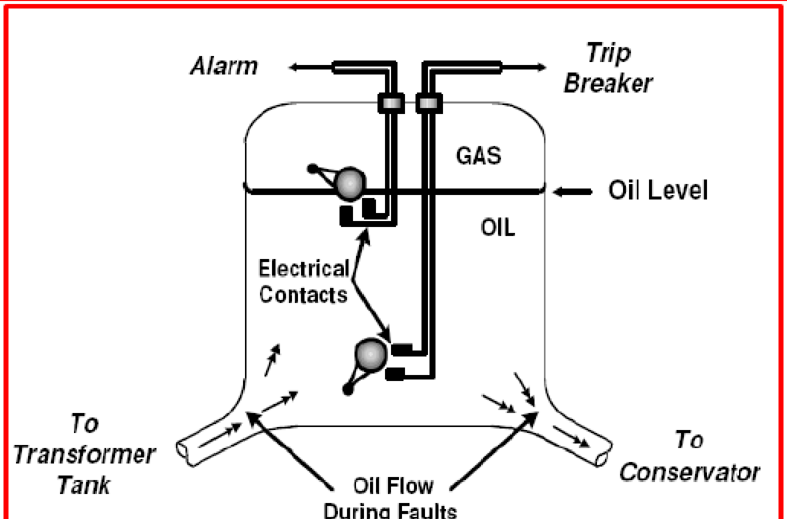


Figure 46: Schematic Diagram of a Buchholz Relay Arrangement

3 Protection فى المحولات

١. أول مشكله تقابلنى مرور تيار طبيعى ساعات مع
اللازم تحويه فيزود الحراره فيعمل حرق حراريا

٢. fault يمر تيارات غير طبيعيه بيقا عاوز اتخلص منها

٣. جهود كبيره تمر تيارات غير طبيعيه اتخلص منها
الأسير

- ارتفاع الجهد بيبوظلك العازل

- ال Tap Changer مش بيقا صفر لأنه يمر فيه تيار الحمل

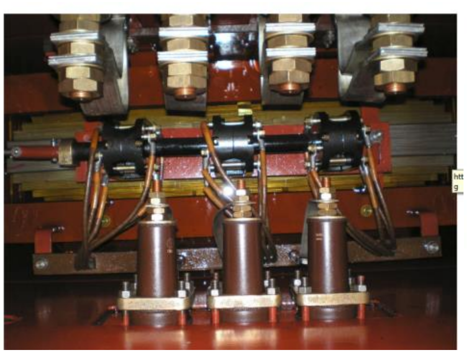
- ساعات لازم تكون موجوده عشان اقدر اشغل ال Trans-

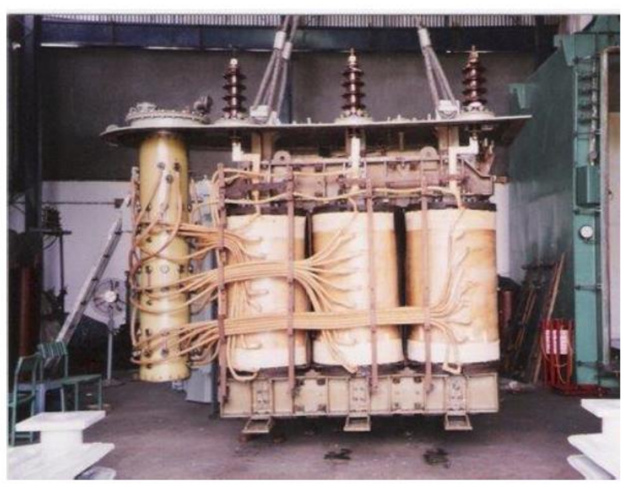
تبريد - وقايه - قياس درجه الحراره - ال alarm - الدايره ال متحل tripping لما الزيت يقل

Tap-Changer

- The tapping may be changed when the transformer is disconnected from the supply. This is called **off-line-tap-changing.** The tapping may be also be changed while the transformer is energized or on load. This is known as **on load tap changing**.

- Daily and short time voltage adjustments are done with the help of on-load tap-changing gear. The off-circuit tap changing is used for occasional adjustments, as in distribution transformers.





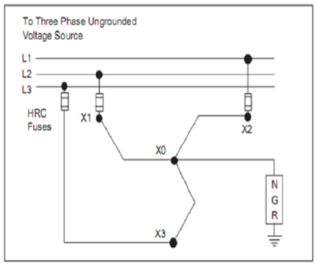
Internal Assembly 15 MVA Power Transformer

Earthing Transformer

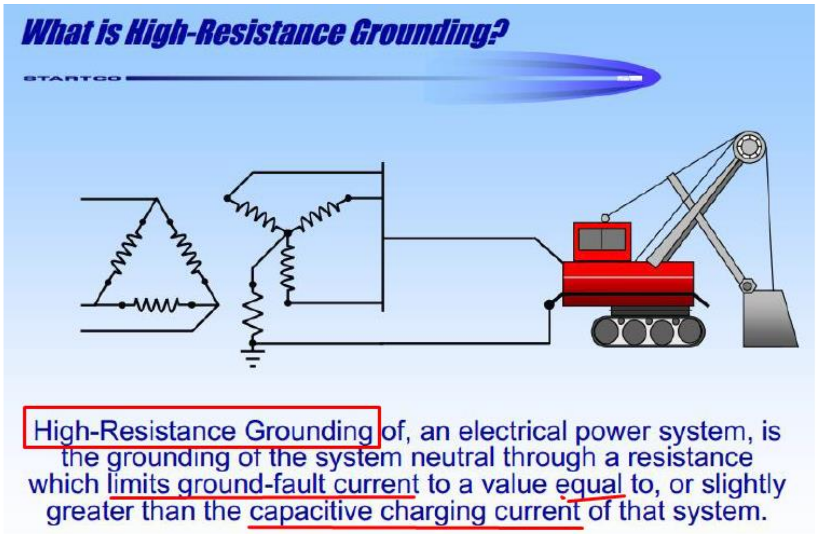
محولات التأريض

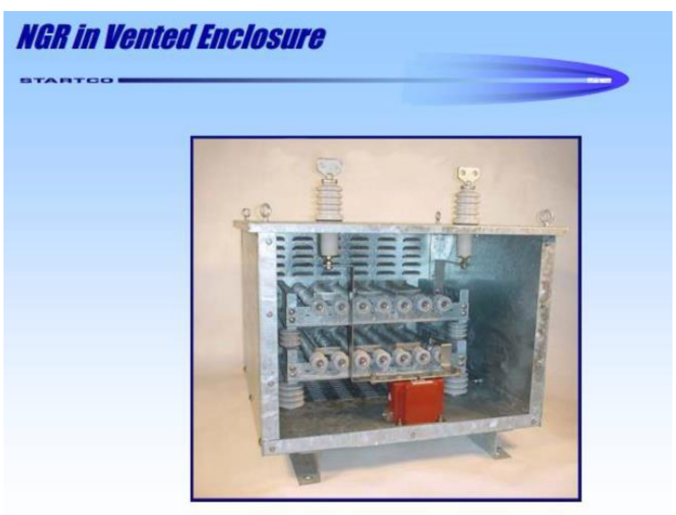
- و تسمى المحولات المساعدة : وهي المحولات التي تكون مرافقة لمحولات القوى الرئيسية ذات القدرة العالية او المتوسطة ، ولها عدة فوائد نذكرها كما يلي:
- تأمين نقطة تعادل للدارة الثانوية في محولات القوى.
- تزويد احتياجات محطة التحويل بالطاقة الكهربائية كالإنارة والتدفئة والتبريد والشواحن ويكون محول التاريض **(Zigzag)** موصولا على شكل Y و بعدها تكون نقطة التاريض إما موصولة مباشرة إلى الأرض أو عن طريق مقاومة.**(NGR)**

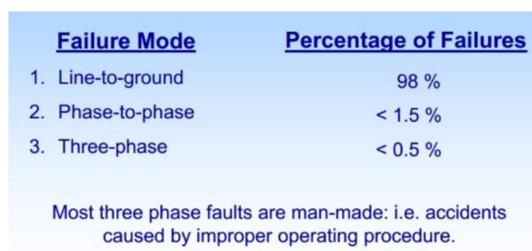
- ممرا للتيار عن **(zigzag)**فعند حدوث عطل , يوفر طريق**NGR.**



NGR (Neutral Ground Resistance)

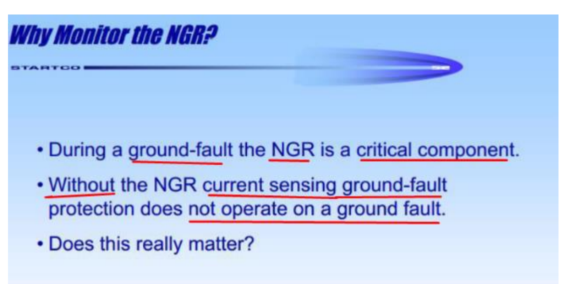




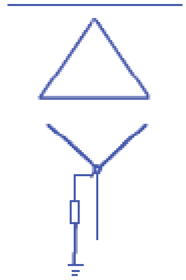
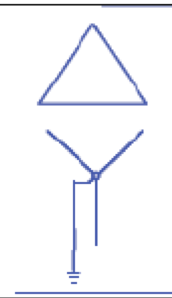
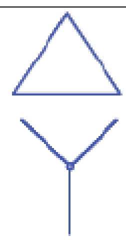
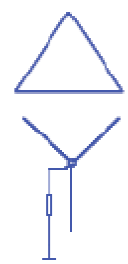


Failure Mode	Percentage of Failures
1. Line-to-ground	98 %
2. Phase-to-phase	< 1.5 %
3. Three-phase	< 0.5 %

Most three phase faults are man-made: i.e. accidents caused by improper operating procedure.

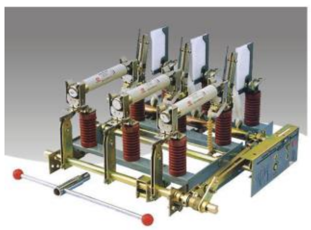


In 98 out of every 100 electrical faults the protection system will not operate as designed with out the NGR.

High Resistance Grounding	**Solidly Grounded**
	
➢ Fault current between 1 & 5 amps ➢ Fault damage unlikely if only one ground ➢ Service continuity – rarely trips ➢ Transient overvoltage eliminated ➢ No arching ground fault ➢ Fault locating by pulsar testing	➢ High magnitude fault current only ➢ Severe fault damage ➢ Poor reliability on essential circuits ➢ Transient overvoltage effectively eliminated ➢ Susceptible to arching faults – needs relay ➢ Self locating by tripped breaker
Ungrounded (rarely used)	**Low Resistance Grounding** (rarely used)
	
➢ No fault current if only one ground ➢ Fault damage unlikely if only one ground ➢ Overvoltage can build to 600% of RMS ➢ Somewhat susceptible to arching faults ➢ Difficult fault location and requires immediate attention before another fault	➢ Fault current between 15-150 amps ➢ Extensive fault damage ➢ Allows for alarms but small circuits trip ➢ Effectively limits transient overvoltage ➢ Severe arching faults are possible ➢ Fault location is very difficult

Protection of Power Transformers

- Fuses are often used for protecting power transformers rated up to 10 MVA or higher if suitable fuses are available. They cost much less than the protection systems and they require little maintenance. Self-powered-resettable fault interrupters can be used for transformers rated more than 10 MVA, and up to 80 MVA, and of appropriate voltage rating. These fault interrupters are similar to fuses, but have the ability to sense neutral current as well to trip all three phases. Clause 8.1 of the guide provides a detailed explanation of selection and operation of fuses and resettable interrupting device.

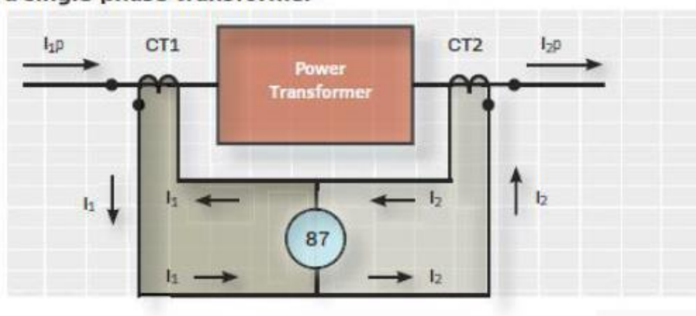


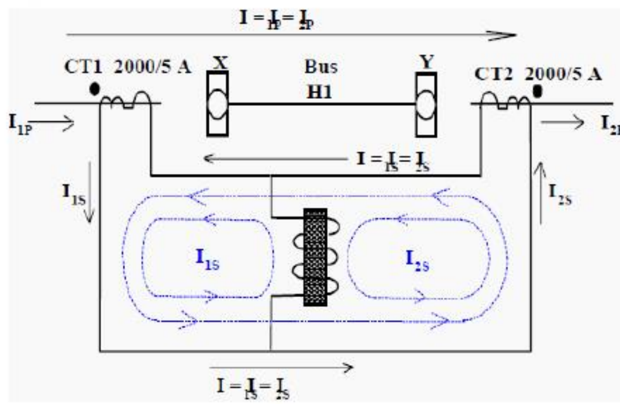
Over current protection

- ***Time over current relays*** provide protection similar to fuses in the event of transformer faults and also provide thermal overload protection to a certain degree. The relay characteristic selected for an application should be below the transformer thermal and mechanical damage curves as discussed in Annex A of the guide.
- ***Instantaneous over current relays*** provide fast clearing for severe internal faults. These are set not to overreach for faults on the low side of the transformer - typically set to 175% (125-200% range) of the calculated maximum fault current for a three phase fault on the low side of the transformer. Clause 8.3 of the guide discusses coordination issues and the currents seen by high side relays for various faults on Delta/Wye transformers.

Differential relays

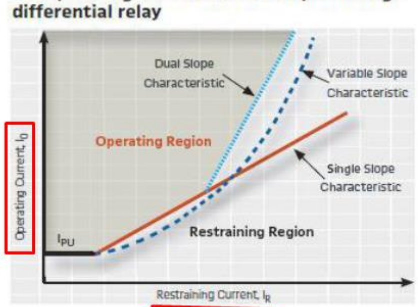
3 Typical connections of a differential relay applied to a single-phase transformer

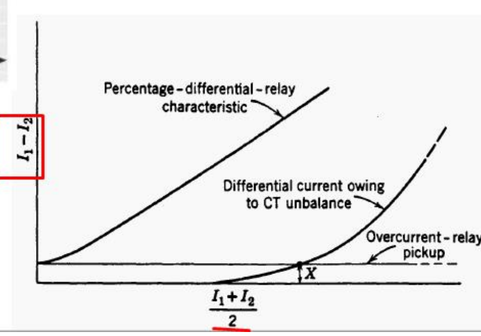




<u>Differential Relay C/C</u>

4 Operating characteristics of percentage differential relay





Measuring temperature rise

- The core temperature is measured with a thermometer, with readings taken with the transformer "cold" and "hot."
- With these two readings, the temperature rise is calculated.
- For example, if we have a reading of 25 [degrees] C "cold" and 75 [degrees] C "hot," then the temperature rise is 50 [degrees] C.

Average Temperature Rise

- The average winding temperature rise is determined by measuring the resistance of a winding when it's "cold" and again when the winding temperature has stabilized under full load. From the difference in the resistance readings, the average temperature is calculated for each winding.

Hot spot temperature

- Although, the resultant temperature rise is averaged over the whole winding, the inside of a winding is hotter than its outside, in reality. The hottest spot is at some point inside the coil having the longest thermal paths to the outside air. This hot spot temperature differential is determined by the manufacturer on prototype units; it's usually expressed as a temperature increase over the average temperature.

- The hot spot temperature differential is defined by industry standards (NEMA and ANSI) for each insulation class (type and temperature rating of insulation used on windings). Obviously, the hot spot temperature is the limiting temperature for a transformer's insulation system. In other [TABULAR DATA OMITTED] words, the temperature rise must be limited by design and application so that the total temperature does not exceed the temperature rating of the insulation used.

EXAMPLE

- if an insulation is rated at 105 [degrees] C maximum, the manufacturer must allow a 10 [degrees] C differential between average and hot spot temperatures in a winding. If the room ambient is 40 [degrees] C, then the allowable temperature rise is as follows.
- Average rise = 105 [degrees] C (hot spot) minus 10 [degrees] C minus 40 [degrees] C (ambient) = 55 [degrees] C

  AVERAGE RISE = 105 - 10 - 40 = 55
- Thus the transformer must be capable of withstanding a 55 [degrees] C average temperature rise.

Impregnation

- Many types of insulation must be impregnated with a treating varnish to improve their 1 temperature rating, 2 resistance to moisture, or 3 dielectric and mechanical strength. The coils also must be impregnated.
- A good impregnating material will fill many of the small holes in a winding: For example, the space between and around two round wires. Impregnation also seals the edges of the coil and, in general, prevents the entrance of moisture and air.
- Filling these small holes eliminates small pockets and, in general, improves the conduction of heat out of the coil.
- The completed core-and-coil assembly then is treated; this molds the complete assembly into one solid mass. Thus, the coils can't move the core, so mechanical wear on the insulation is minimized.

- The core laminations are cemented together by the varnish in this process, thus improving their mechanical strength while preventing movement of individual laminations. This helps reduce the sound level.

Tests during manufacture

1) Core-Plate checks

- ***Core-plate checks.*** Incoming core plate is checked for thickness and quality of insulation coating. A sample of the material is cut and built up into a small

2) Core-frame insulation resistance.

Core-frame insulation resistance. This is checked by Megger and by application of a 2 kV r.m.s. or 3 kV DC test voltage on completion of erection of the core. These checks are repeated following replacement of the top yoke after fitting the windings. A similar test is applied to any electrostatic shield and across any insulated breaks in the core frames. Many authorities consider that for large transformers a test of the core and core-frame insulation resistance at 2 kV r.m.s. or 3 kV DC is not sufficiently searching. Modern processing techniques will enable only a very small physical dimension of pressboard to achieve this level under the ideal conditions within the manufacturer's works. The core and the windings supported from it can have a very large mass so that relatively minor shocks suffered during transport can easily lead to damage or dislocation of components.

3) Core-loss measurement:

Core-loss measurement: If there are any novel features associated with a core design or if the manufacturer has any other reason to doubt whether the guaranteed core loss will be achieved, then this can be measured by the application of temporary turns to allow the core to be excited at normal flux density before the windings are fitted.

4) Winding copper checks.

- ***Winding copper checks.*** If continuously transposed conductor is to be used for any of the windings, strand-to-strand checks of the enamel insulation should be carried out directly the conductor is received in the works.

5) Tank tests

- ***Tank tests***. The first tank of any new design should be checked for stiffness and vacuum-withstand capability. For 275 and 400 kV transformers, a vacuum equivalent to 25 mbar absolute pressure should be applied. This need only be held long enough to take the necessary readings and verify that the vacuum is indeed being held, which might take up to 2 hours for a large tank. After release of the vacuum, the permanent deflection of the tank sides should be measured and should not exceed specified limits, depending on length. Typically a permanent deflection of up to 13 mm would be considered reasonable.

6) FINAL TESTS

- ***Tests to prove that the transformer has been built correctly.*** These include ratio, polarity, resistance, and tap change operation.
- ***Tests to prove guarantees***. These are losses, impedance, temperature rise, noise level.
- ***Tests to prove that the transformer will be satisfactory in service for at least 30 years.*** The tests in this category are the most important and the most difficult to frame: they include all the dielectric or overvoltage tests, and load current runs.

TEST

All transformers are subjected to the following tests:

1. Voltage ratio and polarity.
2. Winding resistance.
3. Impedance voltage, short-circuit impedance and load loss.
4. Dielectric tests.
   (a) Separate source AC voltage.
   (b) Induced overvoltage.
   (c) Lightning impulse tests.
5. No-load losses and current.
6. On-load tap changers, where appropriate.

Type Test

Type tests are tests made on a transformer which is representative of other transformers to demonstrate that they comply with specified requirements not covered by routine tests.

1. Temperature rise test.
2. Noise level test.

Special Tests

Special tests are tests, other than routine or type tests, agreed between manufacturer and purchaser, for example:

1. Test with lightning impulse chopped on the tail.
2. Zero-sequence impedance on three-phase transformers.
3. Short-circuit test.
4. Harmonics on the no-load current.
5. Power taken by fan and oil-pump motors.

The requirement for type or special tests to be performed, or for any tests to be performed in the presence of the purchaser or his representative, must be determined for particular contracts.

Transformer enquiries and tenders

In the initial stage of an enquiry for a transformer there is nothing so important as a full and explicit statement of the total requirements that, from the user's point of view, have to be met and, from the manufacturer's standpoint have to be considered. This statement generally constitutes the *technical specification*, *guarantees and schedules*, which, together with the commercial and contractual conditions, will form the basis of a contract between the user and the supplier.

- It should be clear that if it is required that a manufacturer submit his most competitive tender, in response to any transformer enquiry, a fairly detailed specification defining minimum standards must be issued with that enquiry, otherwise a manufacturer may be justified in making his own assumptions with regard to minimum requirements in the interests of competitiveness.

- Minimum standards can and should, therefore, be identified by the purchaser without restricting a manufacturer's scope for using his expertise to provide reliable and competitive designs. It must be possible, however, to establish compliance with these minimum standards by means of simple checks or tests and not by attempting to dictate to a manufacturer how a transformer should be designed.

Preparation of the technical specification

The first step in the preparation of the technical specification is to draw up a checklist of important technical parameters. This checklist may well take the form of a *schedule of technical particulars* which can ultimately form part of the enquiry document. If the user is in the habit of buying transformers at fairly frequent intervals the form of this schedule can provide the basis for a standard company document. A typical schedule is shown or, alternatively, the appendix listing information required with an enquiry and standard order may be used as a starting point.